Topology Control Algorithms: a qualitative study during the sensor networks life*

Karel Heurtefeux, Fabrice Valois
ARES INRIA / CITI, INSA-Lyon, F-69621, France
Email: firstname.lastname@insa-lyon.fr

Abstract

The goal of the self-organization is to structure the wireless sensor networks (WSN) using a connected logical topology (backbone) or a non connected one (clusters) in order to introduce stability and robustness. More, networking protocols based on such virtual structures should lead to better performances than the classical flat approach. A lot of studies deal with performance evaluations of virtual topologies in terms of energy consumption, cardinality, etc. But the network is mainly 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 robustness, the latency and the cardinality of the main self-organization strategies: i) *dominant-based strategies which select a subset of nodes as dominants,* ii) *link-pruning strategies which select all the nodes and a subset of links. We study the evolution of these schemes during the chaotic deployment of the network (birth phase), the working life and the death of nodes.*

1 Introduction

To manage WSN, we must be able to build a bridge between the intrinsic constraints of the sensors nodes and the applications which we want to carry out. Two approaches can be considered: firstly, networking protocols are based on a flat network where all the nodes are assumed to be equivalent. However, the scalability remains only a dream, it is difficult to cope with the heterogeneity, and more networking protocols are involved (unicast routing, broadcast, etc.) more the overheads are important. The alternate approach is to design a virtual structure, a self-organization scheme, than can leverage several protocols [TV04]. A logical view of the physical topology is build whereas networking protocols and applications are more efficient. Localized protocols are used to provide robust self-organization schemes. Such schemes take advantages of the heterogeneity in terms of nodes density, mobility, energy level, etc. In this work, we study the behavior of several self-organization schemes: link-pruning strategies like RNG [Tou80] and dominant-based strategies like CDS [AJV02]. In the first case, all the nodes and only a subset of the links are in the organization. In the second case, only a subset of connected nodes are in the organization.

There are many interests to create a virtual structure. The diffusion of the control traffic for example, is an important problem since it requires to reach all the nodes. A virtual backbone can be used to forward the packets in a more reliable way. With this simple mechanism it is possible to reach all the nodes without overloading the network: the broadcast storm problem is avoided. More, a virtual backbone allows a simple and efficient sleeping mode: while the dominated nodes are sleeping, the dominants store the data packets arriving and when a dominated is waked up, the packets are transmitted. Finally, a virtual backbone can also be used to provide a scalable and robust routing protocol [TV05]. The selection of only a subset of links in the WSN allows to save energy: topology control allows to support the shortest links and thus the less expensive in terms of power consumption [CISRS03].

We focus our qualitative evaluation on four protocols which are representative of the main strategies to create a connected dominating set (MPR, MPR-DS, CDS-*rule k*, CDS-MIS) and two protocols to represent the main strategies of links-pruning (RNG, LMST). In our point of view, the characterization of these six strategies is the first step toward a possible adaptability of these virtual topologies: a dynamic transition of a scheme to another one according to the state of the network. What does characterization means? We try to exhibit the differences between the protocols when the network evolved because of nodes deployment, the use of sleeping mode or the death of nodes. We define three phases: the birth linked to the (chaotic) deployment, the life where sleeping mode can occurs and the death where nodes are definitively switched off because of a lack of energy. The question which we wish to answer is: are all organizations equal during these phases?

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The paper is organized as follows. Next, some prior works about self-organization schemes and performance evaluation are reviewed. Then, we define the three phases. The assumptions we made and the algorithms we are focused on are presented in section 4. The results we obtained are discussed in section 5. We conclude this work with some future work directions in section 6.

2 Related works

In the dominant-based self-organization protocols, the number of dominants should be minimal in order to reduce the number of transmissions during a flooding and also the overhead. Because wireless sensor nodes are energy-constrained, this problem remains important. Because the computation of a minimum connected dominating set is a NP-complete problem, heuristics are used to provide a trade off between the cardinality of the dominating set and the computation of a dominating set in a distributed way.

In the links-pruning self-organization protocols, the efficiency is generally determined by two criteria: the number of edges and loops in the network in one side, and the range of the selected links on the other side. All the nodes must be connected with the less possible links or using the *best* links in terms of energy saving for example.

2.1 Dominant-based strategies

[QVL02] introduces the Multi Point Relay (MPR) algorithm and a heuristic of complexity $\log n$ to calculate the MPR set for a network cardinality of n. The impact of the error rates due to the radio interface in the case of a blind flooding and a flooding using MPR are evaluated. An analytical study to compute the probability for a node to be a MPR is also given. However, MPR are not compared with other self-organization algorithms, even for the improvement of the flooding only. [SSZ02] provides the main results in the performance evaluation and the comparison of self-organization protocols. The Neighbor Elimination Scheme (NES) mechanism is introduced and several self-organization schemes are also improved. Thus, several metrics are computed (cardinality of the dominating set, degree of the dominating nodes, the redundancy (number of identical packet received by dominated and dominant), overhead). However, the robustness is not studied. In our work, we are mainly focused on the evaluation of the robustness.

[AJV02] is focused on the computation of a dominating set using the MPR. The MPR-DS's cardinality and the number of dominants by dominated nodes are computed. Few comparisons with other self-organization algorithms are provided.

[WD03] is an improvement of the Wu & Li's algorithm to compute a CDS. The rules 1 and 2 are replaced by the *rule k*. This new rule is compared to other algorithms and to the use of the combination of rules 1 and 2. Considering a constant degree, by increasing the number of nodes, the rule k leads to the best cardinality. One of the originalities of this work is to take into account asymmetric radio links.

[WAF02] constructs first a maximum independent set and then a CDS. The CDS-MIS offers a trade-off between cardinality and robustness. The CDS-MIS's cardinality is always bounded by 8 times the cardinality of the MCDS. To deal with the robustness, a maintenance algorithm is proposed.

[BMP04] presents a virtual backbone exhibiting a compromise between the cardinality of the dorsal and robustness. However, if the backbone disconnection is more rare than using others protocols, the reconstruction is not necessarily local. Several metrics are computed: the average time to initialize the protocol, the overhead of each protocol, the average energy consumption by node, the ratio of dominant nodes, the average length of the paths through the backbone, and it defines the robustness as the average number of defective node leading to a backbone disconnection.

[FK04, TM06] are close works of our study. [FK04] propose an analysis of the behavior of a clustering strategy during the deployment of the WSN: only the initialization phase is studied and there is no result about the working life and the death of the WSN as it is proposed in our work. A WSN is modeled as a quasi-unit disk graph whereas we consider more realistic physical layer in order to introduce incoherencies in the neighborhood. A progressive deployment is also considered. The convergence time is computed and the effect of a synchronous and asynchronous wake-up is studied. [TM06] is more focused on the trade-off between energy-efficient and rapidity of a data dissemination in WSN: this trade-off is studied during the birth phase. The notification time in function of the density is computed and also the number of time-slot required to disseminate a data in the network given a particular energy efficient.

2.2 Link-pruning strategies

[LHS03] provides a protocol to compute a local MST. The LMST topology preserves the network connectivity of the original topology and the degree of any node in the LMST topology is bounded by 6. Moreover, the authors provide comparisons with other links-pruning algorithms.

The RNG and LMST protocols are used in [CISRS03] to improve the broadcast protocols. In this way, the links-pruning protocols aim to reduce transmission range and to save energy while maintaining connectivity. When a node sends a message to all the nodes in the network, the message is transmitted with the minimal transmission power which allows to join its RNG (or LMST) neighbors. Moreover, they use a scheme close to NES to avoid useless retransmissions. A comparison with the centralized protocol Broadcast Incremental Power (BIP) is provided: localized protocols can be competitive compared to centralized ones in terms of the energy saving.

3 The three phase of WSN's life

The observation of a WSN reveals the presence of several distinct phases with particular characteristics: the **birth**, the **working life** and the **death**.

The **birth** phase corresponds to the progressive arrival of nodes during the network deployment. It results a phase where the nodes discover their neighborhood. Each node diffuses *hello* packets to indicate its presence and to transmit information on its state. Incoherencies in the neighborhood's tables of some nodes are observed. Indeed, during their birth, the sensors have generally a partial vision of their neighborhood during the transmission of their first messages. More, because of the progressive deployment, the surrounding appear to be dynamic and evolutionary. This leads to transient errors during the election process of dominant-based self-organization protocols or during the link selections process in the links-pruning self-organization schemes. We observe these incoherencies and the time necessary before stabilizing the logical structure. We determine the latency between the physical birth of the network and its logical birth according to the self-organization scheme.

The phase of **working life** begins as soon as the organized structure is stabilized. This phase corresponds to what we can expect, as well as possible, of the self-organization. We highlight the quality of an organization within this phase by observing the cardinality of the dominant structure or the average degree of the logical topology. The working life phase finishes when there are too modifications in the network due to a new massive deployment of nodes or because of the death of nodes.

Then begins the third and last phase: the **death** phase. When one or several nodes disappear, the rebuilding of the logical topology will be necessary. Because of a certain inertia, the nodes haven't immediately the perception of the death of a neighbor. This last phase can be assimilated to the self-healing process.

4 Model and assumptions

4.1 Modeling

All the results we provided here, are computed using simulation tools with a confidence interval of 95%. We use two kinds of tools. First, we consider a simulator with an ideal physical layer and an ideal MAC layer: there is neither interferences nor collisions. In the second case, we use JiST/SWANS: a classical physical layer is modeled with a path loss to model the fading effect and a CSMA-like MAC layer is also used. The differences between these two approaches are important. More realistic simulations introduce non-persistent vicinity and packets loss: thus, there are more incoherencies in the neighborhood. The network cardinality varies between 50 and 200 nodes, uniformly distributed in the simulation area. The transmission power is used to control the average degree of the network. The objective is to observe how the the environment influences the construction of a logical topology. We noted that only the average degree of the nodes and its cardinality plays a significant part. The sensor nodes are not synchronized and they are switched on one by one during the deployment. The identity of each sensor is determined by a single identifier in the various algorithms using this metric for the election of dominating nodes. Each sensor is regarded as fixed.

4.2 The four dominant-based self-organization protocols

The multipoint relays are used in the OLSR [CJ03] routing protocol. Each node knows both its 1-hop and 2-hop neighborhood. There are several strategies to select MPR: a node u selects as MPR, among its 1-hop neighbors, the node which cover the most 2-hop nodes set. This selection is repeated until the 2 hop-neighborhood is not totally covered. The nodes selected as MPR form a subset of the 1-hop neighborhood of u, and are used to reach all the 2-hop neighborhood of u. To form a dominating set, a source initiates the construction and, then, each MPR node of this source calculates its MPR nodes and so on.

MPR-DS [AJV02] proposes to construct a non-oriented source MPR, *i.e.* not initiated by a particular sensor node. MPR-DS algorithm is carried out in two steps. Thus each node need to determine its status: *dominating* or *dominated*. During the first step, if a node is a local minimum according the smallest identity in the neighborhood, it becomes a dominating node. Thus, at the end of the first step, an independent set in the WSN is computed. The second step integrates a node as a dominating set if the node is a MPR of its smallest neighbor. At the end of the second step the dominating set is connected and forms a backbone.

The CDS-*rule k* [WD03] algorithm also breaks up into two phases. The first phase -*marking process*- colors in black the nodes according to the rule: a node u is selected if there exist v and w, two neighbors of u, such as both (w, u) and (u, v) exist but (w, v) does not exist (w is not a neighbor of v). In the case of symmetrical links, the marking process selects a node which have at least two of its neighbors which are not neighbors. The second phase, the *rule k*, is an improvement of the previous rules 1 and 2.. It eliminates nodes selected too coarsely during the first phase. For each node

u, the neighbors of u which are colored in black and with an higher identifier than u are selected. Then, the rule determines the strongly related sets resulting from these nodes and looks if one of these sets covers the whole neighborhood of the node. If it is the case the node is in the dominating set. The *rule k* is proposed in two forms: the restrictive form and the non-restrictive form. The first one is limited to the knowledge of the directly close related groups, whereas the second one can traverse the entire graph. We focus on the restrictive form only.

The CDS-MIS algorithm [WAF02] is carried out in four phases: the election of the leader, the computation of the levels of the nodes in the tree where the leader is the root, the coloring of the dominant nodes and finally the construction of the dominating tree. The leader election chooses the node of the network which will initiate the calculation of the levels: it can correspond to the sink of the WSN. In the second phase each node determines its level in the tree using local rules. The third stage of the protocol colors the nodes, all white at the origin, in gray (for dominated node) and in black (for the dominating node) in such way that the set of dominating node forms a Maximum Independent Set(MIS). The last stage connects the black nodes to form a CDS.

4.3 The two links-pruning self-organization protocols

The Relative Neighbor Graph (RNG) [Tou80] is based on the knowledge of the location of the nodes. Indeed, each sensor node knows its position and diffuses it to its direct neighbors. Thanks to the position of the 1-hop neighbors, a node removes the longest links in the following way: given two neighbor nodes u and v, if there is a node w such as $d(u, v) > d(u, w)$ and $d(v, u) > d(v, w)$ then the edge (u, v) are deselected. gray area. In this way, the connectivity of the original graph is preserved and the shortest links in the network are preferred.

[LHS03] allows to compute the Local Minimum Spanning Tree (LMST). Each node knows the location of its 1-hop neighbor and each node computes a MST in its neighborhood. The construction of the LMST topology is based on the construction of local MST by each node. An edge (u, v) is in the final LMST iif v is in the LMST(u) and u is in the LMST(v).

5 Results

Our goal is to show the behavior of the 6 previous self-organization schemes on evolving networks. The latency is measured, *i.e.* the duration between an unsteady topology and a steady one. To measure the *quality* of the protocols, we compute the cardinality of the dominating set for dominant-based protocols and the average degree for the links-pruning protocols. To understand the consequences of a disappeared node, we compute the number of nodes changing their statute and also their distance from the death node. This metric is useful to understand if, despite these protocols are localized, the self-healing is only local or not. In our point of view, these metrics allow to characterize the different self-organization schemes during the WSN evolution (birth, life, death).

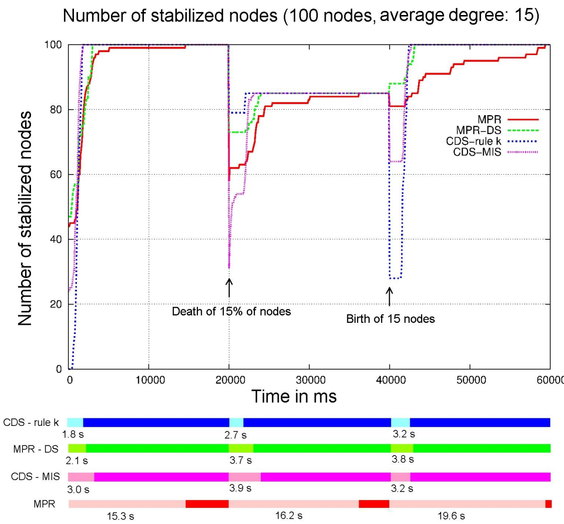

Figure 1. Latency of the 4 dominant-based self-organization schemes

5.1 WSN deployment

The construction times of the logical topologies (birth) are quite different according to the dominant-based self-organization schemes (Fig. 1). Whereas the nodes discover their vicinity in less than 1.8 seconds, the logical topology of MPR will take more than 18 seconds before becoming stable (for an average degree of 15 nodes). On the other hand, the other schemes will be faster by completing the construction of their dominating set in few seconds. The average degree of the nodes has an impact on the construction time: more the average degree is high and less the height of the virtual backbone is important. The time to cover the tree and to elect the dominating nodes is reduced. For both the MPR-DS and the CDS-*rule k*, this construction time remains identical whatever the average degree because the election of dominating nodes is purely local. We can note, however, that the construction of a backbone using CDS-*rule k* requires a phase where at least 80% of the nodes are preselected like *dominating* before to become dominated. This passage from one status to another one could be energy consuming.

The construction of the links-pruning topologies are much faster. The logical birth of the network, *i.e.* the construction of logical topology, corresponds exactly to the physical birth of the network, *i.e.* the discovery of the whole neighborhood of each sensor. Thus the logical birth are very fast, about 1.8 seconds for a network of 100 nodes (Fig. 2). Using these metrics, the two links-pruning schemes are close. The speed with which the sensors determine their logical neighbors, those with which they keep links, is only related to the speed to which the neighbors send their hello packets.

The quality of the links-pruning protocols during the working life phase is determined by the quality of the selected links and the connectivity of the network. Both RNG and LMST protocols guarantee the connectivity of the network. However RNG is slightly more powerful: for an average physical degree of 18, it keeps on average only 2.4 links toward the neighbors whereas LMST keeps on average 2.6 links toward its neighbors.

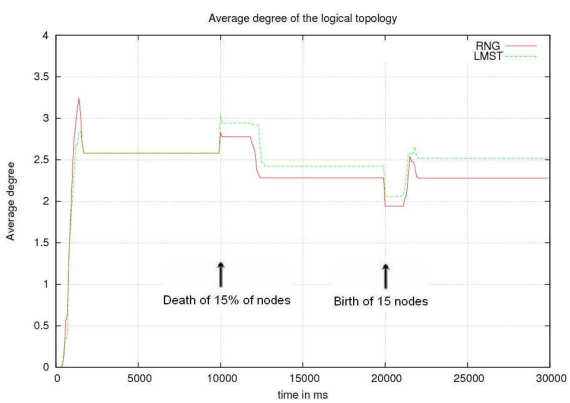

Figure 2. Evolution of the average degree of the LMST and RNG logical topology

5.2 Logical topologies adaptation: robustness

One of the objectives of WSN is their capacity to be deployed quickly under difficult conditions. This means that, without robustness, the sensor network lost its principal interest. To measure the robustness, we remove a variable percentage of nodes (links, resp.) of the WSN, among the dominant and dominated nodes (selected links, resp.) for the dominant-based (links-pruning, resp.) protocols.

For the dominant-based protocols, the same tendencies as on Fig. 1 is highlighted whatever the nature of the removed nodes. The loss of a dominating node has always more consequence than the loss of a dominated node: the CDS-MIS is far from resistant to the death of sensors in

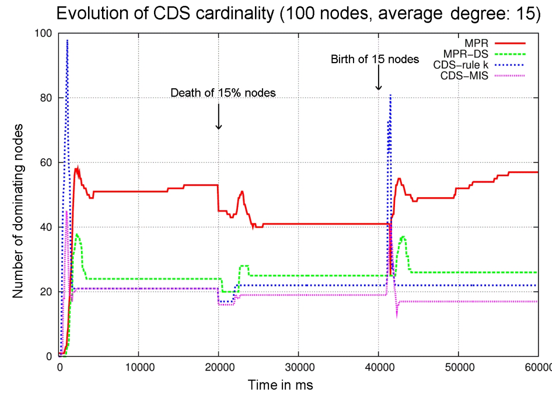

Figure 3. Evolution of the cardinality of the connected dominating set

particular for the medium and small degrees, but a new stable structure is found quickly. The MPR is more robust in terms of topology change but finds a stable structure very slowly after the loss of the nodes. The MPR-DS and the CDS-*rule k* behave suitably against the loss of node: their structure is changed locally and their structure finds stability quickly. For a given network cardinality, a WSN with a higher average degree will be more robust whatever the self-organization protocols used. The reason of the structural weakness of the MPR and the CDS-MIS is the construction in a tree of their dominating set. If this structure allows a low cardinality of the dominating set for the CDS-MIS [WAF02], the initialization of construction by a source node involves a great brittleness: if a dominating node near to the source changes its state, all the branch of the tree should be potentially rebuild. Thus, according to various simulations carried out, the number of changes at the time of the loss of nodes MPR is relatively important. When a node of the backbone is removed, the average number of affected nodes is more than 3 and the average range is 1.70 hop. A similar behavior is noted for CDS-MIS with an average of more than 13 nodes whose is amended and a range is 1.70 hop. This means that the loss of only one dominating node involves an important topological modification of the backbone at the same time in terms of a number of modified nodes but also in terms of distance with the dead node. Here again, the construction in a tree of the dominating set is blamed. Moreover, the very low cardinality of a dominating set using CDS-MIS suggests a greater importance of the dominating nodes because the redundancy is weak. CDS-*rule k* protocol behaves in a very satisfactory way in the two aspects, while MPR-DS protocol undergoes a localized change of the topology in the 1 hop of the lost node. (1.1 nodes changing on average on a medium radius of 1.1 hop for the CDS-*rule k* and 2.4 nodes changing on average on an average radius of 1.08 hop for the MPR-DS).

The behavior of the links-pruning protocols is different. In those protocols, the sensors do not share their neighborhood table between them and the incoherencies are thus impossible. In consequence, the disturbances due to the lost of a node are very limited and totally localized. Moreover the average degree of the network does not play any role in the robustness because the LMST or the RNG graph is almost the same whatever the power transmission of the nodes is.

The average number of topology change using RNG is equal to 1.7. The propagation of the loss of a node is purely local and thus equal to 1 hop on the logical topology, *i.e.* only the incidental edges with the neighbor nodes in RNG are potentially modified (Fig. 4). The behavior is similar for LMST protocol in terms of average number of changes (1.8). The range of the modification remains purely localized if we look at the physical topology. For those two protocols the modification have potentially an influence with several hops distance in the logical topology (Fig. 5). We can observe this case when a dead node is used as bridge between a node and another one.

Thus, the RNG protocol is more robust than LMST, even if the differences in case of small transmission ranges are negligible. However RNG selects the links between the nodes only according to their distance, LMST is able to select them with another metric.

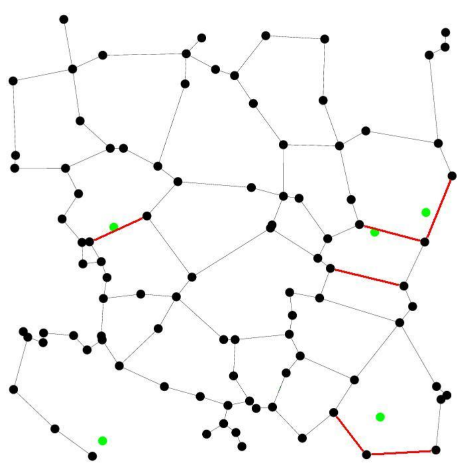

Figure 4. RNG topology changes against the death of nodes

To illustrate these results, let's observe the Fig. 6 and Fig. 7. They represent the modifications of the logical topology when dominating and dominated nodes die. Fig 6 is the logical topology when CDS-MIS is used. The green nodes are the tree roots, the surrounded nodes are the dead nodes and the links in red are the links which are disturbed by the death of node. In this case, we can note that disturbances are far from the dead nodes. In fact, the changes can be propagated until the end of a branch of the tree. On the other

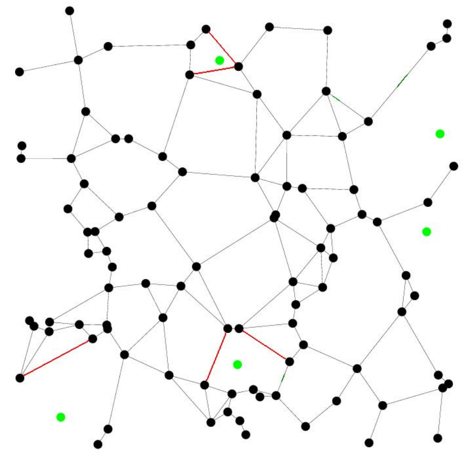

Figure 5. LMST topology changes against the death of nodes

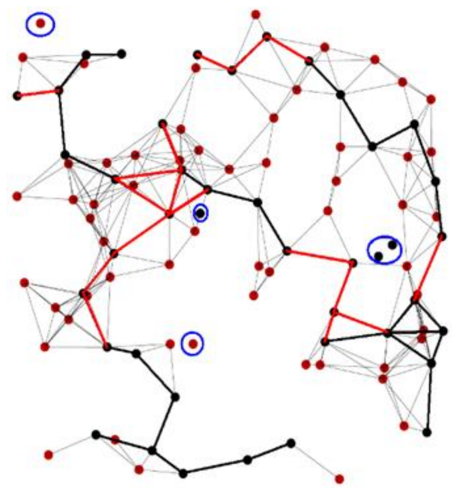

Figure 6. CDS-MIS topology changes against the death of nodes

hand, the topologies created by the CDS-*rule k* (Fig. 7) react generally by the replacement of the dominating node by a 1-hop neighbor. The disruptions are localized.

We also observe the behavior of the self-organization schemes when a new node arrives whereas the logical topology is built. In this scenario, the CDS-*rule k* is extremely ineffective because its initial phase, the *marking process*, over selects nodes on dominating set. Then the second phase, the *pruning rule k*, deselects them almost immediately (Fig. 3). That involves a strong variation of the dominating set cardinality at the time of the the network deployment but in a very short duration what makes it possible the protocol to remain effective in terms of latency. The CDS-MIS reacts better but 15 % of the nodes will undergo this change. The MPR and the MPR-DS suffer from almost no change of topology and are satisfied to absorb the new nodes in

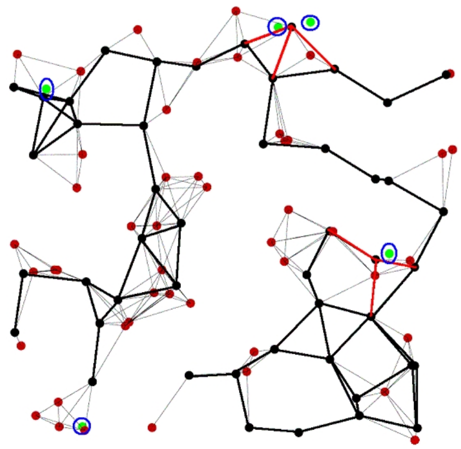

Figure 7. CDS-*rule k* topology changes against the death of nodes

their topology. The average degree of the network will not change these behaviors radically, only the identity of the new nodes can have an influence in the case of MPR-DS whose logical topology will be disturbed by the appearance of a new local minimum.

6 Conclusion

In this work, we propose a qualitative study to understand the behavior of localized protocols during the different phases of the wireless sensor networks life. Three phases are defined: birth, working life and death. We study four dominant-based self-organization protocols (MPR, MPR-DS, CD-*rule k*, CD-MIS) and two link-pruning one (RNG, LMST) during these phases. We also observe how these protocols cope with a new arrival or the death of a node. We compute the evolution of the cardinality and the latency to rebuild a stable connected virtual topology. We note a great robustness against die of sensors of the two link-pruning protocols and the CDS-*rule k* while, at the same time, the appearance of nodes in the network is much more favorable to MPR-DS. However, if the CDS-MIS is not robust, it is the best in terms of cardinality of its dominating set in the phase of working life. According to us, it is now possible to take advantage of these observations to propose a dynamic self-organization scheme which evolved when the network topology evolves too.

The next objective is to study these protocols on WSN testbed. In the ARESA project [DDM$^+$07], we simulate these self-organization protocols while using the characteristics of specific WSN of more 10.000 nodes with the goal of improving the robustness, the power consumption and the speed of configuration.

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