Sensors & Transducers, Vol. 213, Issue 6, June 2017, pp. 9-23

Sensors & Transducers
Published by IFSA Publishing, S. L., 2017
http://www.sensorsportal.com

Deployment Strategies and Clustering Protocols Efficiency

Chérif Diallo
Laboratoire Algébre, Cryptographie, Codes et Applications (ACCA)
UFR Sciences appliquéeset de Technologies (UFR SAT)
Université Gaston Berger, BP 234 Saint-Louis, Sénégal
Tel.: +221339612340, fax: +221339615338
E-mail: cherif.diallo@ugb.edu.sn

Received: 22 April 2017 /Accepted: 31 March 2017 /Published: 30 June2017

Abstract: Wireless sensor networks face significant design challenges due to limited computing and storage capacities and, most importantly, dependence on limited battery power. Energy is a critical resource and is often an important issue to the deployment of sensor applications that claim to be omnipresent in the world of future. Thus optimizing the deployment of sensors becomes a major constraint in the design and implementation of a WSN in order to ensure better network operations. In wireless networking, clustering techniques add scalability, reduce the computation complexity of routing protocols, allow data aggregation and then enhance the network performance. The well-known MaxMin clustering algorithm was previously generalized, corrected and validated. Then, in a previous work we have improved MaxMin by proposing a Single-node Cluster Reduction (SNCR) mechanism which eliminates single-node clusters and then improve energy efficiency. In this paper, we show that MaxMin, because of its original pathological case, does not support the grid deployment topology, which is frequently used in WSN architectures. The unreliability feature of the wireless links could have negative impacts on Link Quality Indicator (LQI) based clustering protocols. So, in the second part of this paper we show how our distributed Link Quality based d-Clustering Protocol (LQI-DCP) has good performance in both stable and high unreliable link environments. Finally, performance evaluation results also show that LQI-DCP fully supports the grid deployment topology and is more energy efficient than MaxMin.

Keywords: Wireless sensor network, Deployment strategy, Multihop Clustering, LQI, MaxMin, LQI-DCP.

1. Introduction

The deployment strategy of sensor nodes in a control zone is cited among the critical points in the design of sensor applications. It tightly depends on the nature of the WSN application and its main objectives [1-4]. The nodes are often either distributed in a predefined manner or randomly (dropped from a mobile system such as an airplane for example).

For some applications precise distribution of the nodes is a requirement for properly functioning. The nodes must be deployed in predetermined positions to ensure efficient network operations as the application results rely on node locations: home medical monitoring of a patient, roads monitoring, operation supervision of industrial systems, etc.

Other applications do not require accurate distribution of the nodes. This is the case of such applications where the sensor nodes could be deployed randomly. This could be due to the environment difficulties (geographical, climatic, etc.): military surveillance of the enemy zone, forest fire monitoring systems, etc.

In a cold chain monitoring application, due to the size of a warehouse which hosts large numbers of pallets, provided each with a temperature sensor, the Wireless Sensor Network (WSN) can reach several hundreds of nodes which collaborate for sending alarms towards the Base Station (BS). This application specifically collects rare events (alarms) to ensure the proper monitoring of the system. If the temperature is over a threshold, an alarm will be generated; this "interesting event" is then sent towards the BS. In such a context, network clustering techniques add scalability feature and then reduce the computation complexity of data gathering and routing protocols [5].

The more often WSN architecture used in cold chain monitoring applications is the grid deployment topology. So, in this paper, we show that one should be careful with the MaxMin clustering heuristic in such a topology.

In [2] and [6], we have shown how it is important to sufficiently outspread clusterheads in order to reduce cluster overlaps, the amount of channel contention between clusters and energy wastefulness due to overhearing phenomenon. The MaxMin clustering heuristic, as proposed in [7-8], has the drawback of not taking into account this problem. In order to solve this issue, we have proposed LQI-DCP in [3]. LQI-DCP is energy efficient LQI based protocol which aims to construct multihop clusters by producing clusters of which each clusterhead has a better positioning regarding the locations of other clusterheads. The clusterheads resulting from LQI-DCP are sufficiently outspread. LQI-DCP also reduces the density of clusterheads and then improves the WSN energy efficiency, while each sensor still remains at most d-hops away from its own clusterhead.

In a cold chain monitoring application, the warehouse hosts hundreds of pallets, one upon the other. This environment is subjected to some unreliability of the wireless links. So, it is important for LQI based clustering schemes to fully support such an environment. This is the main objective of the second part of this paper which completes discussions related in [2] and [3] where the grid deployment topology were not been taken into account. Moreover, our works in [1] did not include energy efficiency analysis which is the third objective of this paper.

Previous works [2, 7-8] present details on MaxMin, whereas LQI-DCP is described in [3]. All clusterhead selection criteria used in this paper are defined in [2-3]. As in [2-3] we indifferently use caryomme(s) or clusterhead(s).

To carry out our work, this paper is organized as follows: in the next section we will present few WSN deployment strategies before describing the MaxMin Pathological Case is in the section III. Consequently, we will explain, in the section IV, why MaxMin does not support the grid deployment topology. Then, in the sections V, we will show how LQI-DCP is well adapted for the grid deployment topology. Finally, the last two parts present performance results pertaining to MaxMin and LQI-DCP clustering protocols when one takes into account the unreliability feature of the wireless links (sections VI & VII) and the energy efficiency of network operations (section VIII).

2. WSN Deployment Strategies

2.1. Random Deployment without Constraint

The sensor deployment on a well-defined collection target could be done randomly, in which case the density might be very different from one location to another [9]. This type of deployment occurs during a bulk jet of the sensors from a helicopter or missile. Many sensor applications use a random deployment without constraint, due either to the hostility of the monitored area or its large size [10].

The use of the random deployment strategy creates the challenge of ensuring good connectivity quality in the network. Wireless links connectivity would be significantly degrading with poor distribution of the sensor nodes over the target area. Thus with this deployment type, some sensor nodes might have been isolated or disconnected. A sufficient quality of connectivity obviously helps ensuring packets routing under right conditions: low transmissions delay, low rate of packet losses, low energy consumption and high rate of successful delivery of messages to the base station.

The random deployment is also well suited for dense sensor networks where the redundancy of the sensors on the monitored area is a required for application accuracy. In such sensor systems, this could help in enhancing network lifetime by putting a certain number of redundant sensors on standby mode while ensuring a full coverage of the monitored area and maintaining a good network connectivity rate [10].

This type of deployment often requires a good clustering protocol to better guarantee good network performance. However, given the density of the network and the number of formed clusters, care should be taken to avoid the creation of single-node clusters which could annihilate network performance [2]. Furthermore, the protocol must be designed to produce clusterheads far enough away to maximize the network lifetime [3].

2.2. Deployment with Remoteness Constraint between Nodes

Another deployment strategy is the deployment with remoteness constraint between nodes. In this type of deployment, the minimum distance separating two nodes is at least equal to $\lambda * R$, where R is the communication radius and λ, $0 \leq \lambda \leq 1$, is the remoteness parameter [9]. If $\lambda = 0$, then this is the case of random deployment without constraint.

This type of deployment could be used in applications where sensors are equipped with GPS, or in indoor industrial applications where node locations are predetermined. Thus the remoteness parameter λ could be chosen in a manner to reduce network density. This will helps in reducing energy losses due to overhearing phenomenon [9].

Another variant of this type of deployment is the deployment of sensors run in a direction with remoteness constraint between nodes [9] which is common for many (military, agricultural, environmental, etc.) applications where nodes are deployed by a robot, vehicle, helicopter or plane in hostile environment where human presence is not easy [9]. In such applications, the remoteness parameter λ and the direction could be tuned according to the speed of the robot, vehicle, helicopter or plane.

This type of deployment responds to the same clustering constraints as the previous one. Except that in this case, the clustering protocol does not have to have as objective to produce clusterheads rather distant from each other because, given the parameter λ, the relative remoteness of the nodes is already ensured in the initialization phase of the network.

2.3. Grid Topology

The grid deployment topology is the most common topology for indoor sensor network architectures, particularly in cold chain monitoring or sensor based security applications. The grid may be uniform or not according to the values of steps used in the abscissa axis and that of the ordinates. Moreover, the positions of the sensors are often predetermined in the grid. Therefore, the clusterheads could be chosen according to their coordinates. This could facilitate the deployment of heterogeneous networks where some sensors, intended to be clusterheads, would have better hardware resources and greater computational capabilities. This would allow them to be positioned from the network start at locations that ensure better network performance. On the other hand, in the case of a homogeneous network with a clustering protocol, this one must be designed to be compatible with the inherent specificities of the grid topology. This is what we shall see in the following.

3. The MaxMin Pathological Case

The MaxMin algorithm is improved by \cite{ADelye},\cite{MMarot} as a generalization of the earlier MaxMin algorithm proposed by \cite{ADAmis}. It takes place in 2d+1 rounds. The first round consists of information exchanges to initialize the algorithm. The following d-rounds are the floodmax phase, which is followed by the floodmin phase composed of last d rounds.

Given the similarities with Linked Cluster Algorithm (LCA) [13] and LCA2 [14], MaxMin naturally inherits the same pathological case. Thus, in the original paper [8] which revealed MaxMin to the scientific research community, the authors reported the pathological case for which MaxMin fails in the process of cluster formation. We reproduce here the figure (Fig. 1) and the argument as they were stated in [8]: *"There is a known configuration where the proposed heuristic fails to provide a good solution. This configuration is when node ids are monotonically increasing or decreasing in a straight line. In this case, the* ***d+1*** *smallest node ids belong to the same cluster as shown in Fig. 1. All other nodes become clusterheads of themselves only. Again, while this is not optimal it still guarantees that no node is more than d-hops away from a clusterhead. Furthermore, this configuration is highly unlikely in a real world application. However, this is a topic of future work to be performed with this heuristic."*

Fig. 1. Worse case performance scenario for MaxMin [8].

In the next section, we will show how this pathological case has negative impacts on the grid deployment topology. Indeed, the authors of [8] said that: *"Furthermore, this configuration is highly unlikely in a real world application"*. This is obviously wrong because the grid deployment topology is more often encountered in real WSN applications, especially in a cold chain monitoring application.

4. MaxMin Incompatibility with the Grid Deployment Topology

To better understand the consequences of the MaxMin pathological case on the grid deployment topology, let us consider the representation in Fig. 2, where N nodes are deployed on a rectangular area of length L and width l. Considering a grid where each side of the area is subdivided with a constant step λ. Then, the coordinates $x(i)$ and $y(i)$ of the i^{th} node $i \in [|1, N|]$ are obtained as follows:

$$n = \left\lfloor \frac{L}{\lambda} \right\rfloor, m = \left\lfloor \frac{l}{\lambda} \right\rfloor, N = ((n+1)*(m+1)) - 1,$$

where $\left\lfloor \frac{L}{\lambda} \right\rfloor$ denotes the integer part of $\frac{L}{\lambda}$

$$x(i) = \lambda * \left\lfloor \frac{i}{m+1} \right\rfloor, y(i) = \lambda * i \, mod(n+1)$$

If we assume that all nodes have the same transmission range ***R* = *2*λ***. Consequently, the sensors 1, 3, 9, 19, 23, 21, 15 and 5 are equidistant from the node 12 and located exactly at the distance **$\lambda*\sqrt{5}$** from the node 12, that is to say, outside the vicinity of the node 12. The same is true for the sensors 9, 13, 11 and 5 with respect to the node 2.Then, by running MaxMin algorithm with the parameter ***d* = *1*** and the function criteria ***f(x)* = *id(x)*** for the WSN example in (Fig. 2), where ***id(x)*** is the number of the node ***x***:

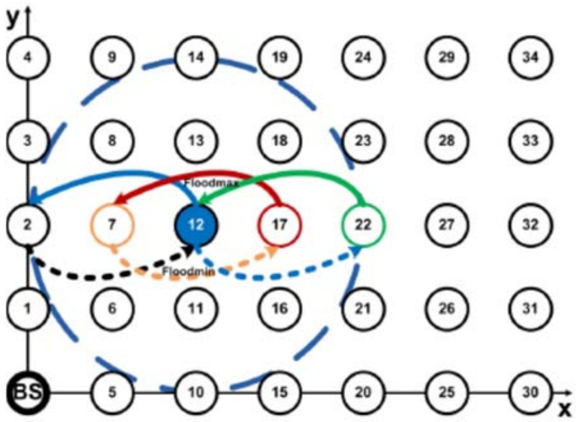

Fig. 2. MaxMin run in a grid deployment topology.

- During ***floodmax*** phase, the node 2 receives the value 12 from 12th node because the node 13 is not in the vicinity of the node 2.

- During ***floodmax*** phase, the node 1 receives the value 11 from 11th node because the node 12 is not in the vicinity of the node 1.

- Next, the node 12 receives this value 12 from 2nd node during the ***floodmin*** phase as the node 1 is not in the vicinity of the node 12.

- Accordingly, the 12th node is selected as clusterhead.

- As far as that goes, all the ith nodes, i ϵ [10, 34], are selected as clusterheads (Fig. 3).

- More generally, it's easy to show that all the ith nodes i ϵ [2(m+1),N] are selected as clusterhead by MaxMin.

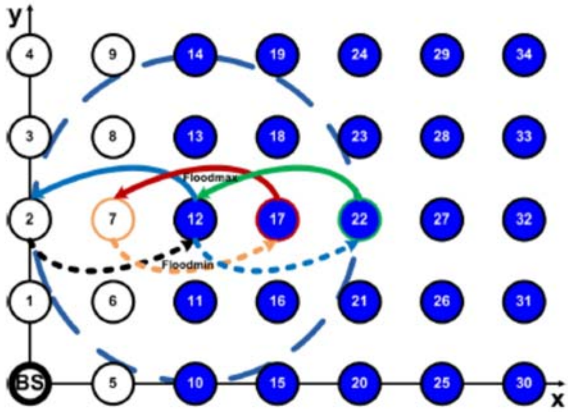

Fig. 3. Consequences of the MaxMin pathological case on the grid topology: with R = 2*λ, from the 3rd column, all nodes are elected caryommes.

The two tables above (Table 1 and Table 2) summarize MaxMin's computation for this network (Fig. 2). Here again we are using the same notations as in [2].

Table 1. MaxMin results with d = 1 for the WSN (Fig. 2).

Node ID	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Floodmax W_1	10	11	12	13	14	14	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Floodmax S_1	10	11	12	13	14	14	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Floodmin W_2	10	10	10	11	12	10	10	11	12	13	10	11	12	13	14	15	16	17	18	19
Floodmin S_2	0	0	0	1	2	0	0	1	2	3	0	1	2	3	4	5	6	7	8	9
Caryomme	10	11	12	13	14	14	16	17	18	19	10	11	12	13	14	14	16	17	18	19

Table 2. MaxMin results with d = 1 for the WSN (Fig. 2) (continuous).

Node ID	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**
Floodmax W_1	30	31	32	33	34	31	32	33	34	34	32	33	34	34	34
Floodmax S_1	30	31	32	33	34	31	32	33	34	34	32	33	34	34	34
Floodmin W_2	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Floodmin S_2	10	11	12	13	14	14	16	17	18	19	20	21	22	23	24
Caryomme	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34

Because of this, given the proximity of the clusterheads produced by MaxMin in this case, it is clear that most of the clusters are single node clusters. We have shown in [2] that this phenomenon of single node clusters is detrimental to the network performance because it considerably increases the energy consumption and thus reduces the lifetime of the network.

Thus, it is important to be careful when one chooses the criteria used to select the MaxMin clusterheads in the context of a grid deployment topology. Indeed, the "degree of connectivity" and "MinLQI" criteria also suffer the same effects because of the smoothness of the grid topology. These criteria are monotonically increasing in each row and each column of the grid when one moves from the edge toward the center of the deployment area.

Thus, MaxMin run with the Single-Node cluster reduction mechanism (SNCR) [2] leads to the following results for criteria: "Node id" (Fig. 4), "Degree of connectivity" (Fig. 5), and "MinLQI" (Fig. 6). These results are explained by the neighbourhood relationship (transmission range) between the selected clusterheads.

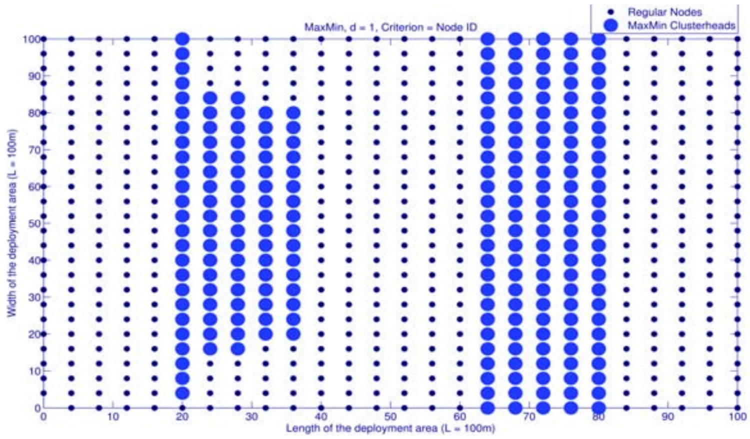

Fig. 4. MaxMin: Average clusterhead locations, Node ID criterion, d = 1.

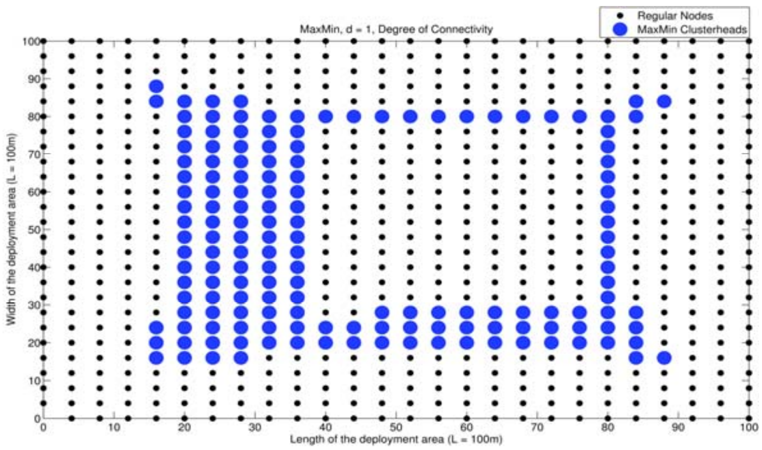

Fig. 5. MaxMin: Average clusterhead locations, Degree of Connectivity criterion, d = 1.

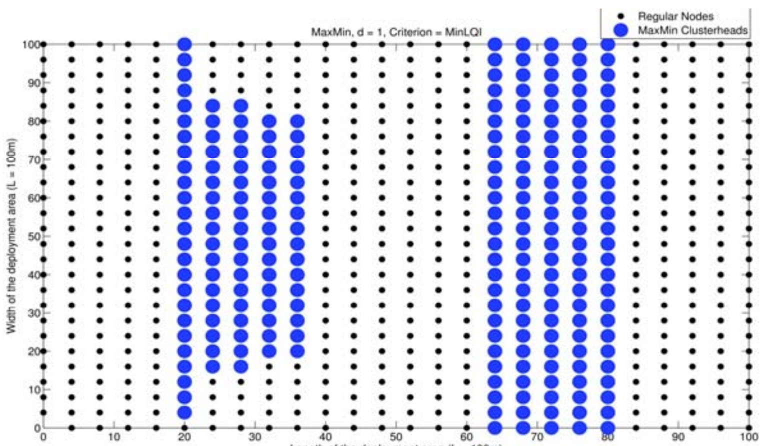

Fig. 6. MaxMin: Average clusterhead locations, MinLQI criterion, d = 1.

So, we obtain a series of clusterheads located in adjacent columns which are periodically separated by adjacent columns composed of regular nodes (Fig. 6).

To overcome this issue of MaxMin pathological case in a grid deployment topology, one should choose a criterion function of which the values are randomly distributed to the nodes. This helps avoiding a function which is monotonically increasing (or decreasing) along the lines of the grid. This randomization of the criterion overcomes the problem of MaxMin pathological case (Fig. 7) but also has the disadvantage of leading to unpredictable results. Indeed, the benefit of choosing a particular criterion rather than another one is to promote optimal results with respect to the main objectives of the application according to its operational conditions. (Fig. 7) shows the location of caryommes obtained for a randomized function criterion. As we can see, this result is not optimal because some clusterheads are too closely located. Therefore, this leads to high energy consumption because of overhearing, channel contention and overlaps between clusters [2].

The MaxMin pathological case is also a big drawback for multihop clusters, $d \geq 2$, as shown in (Fig. 8).

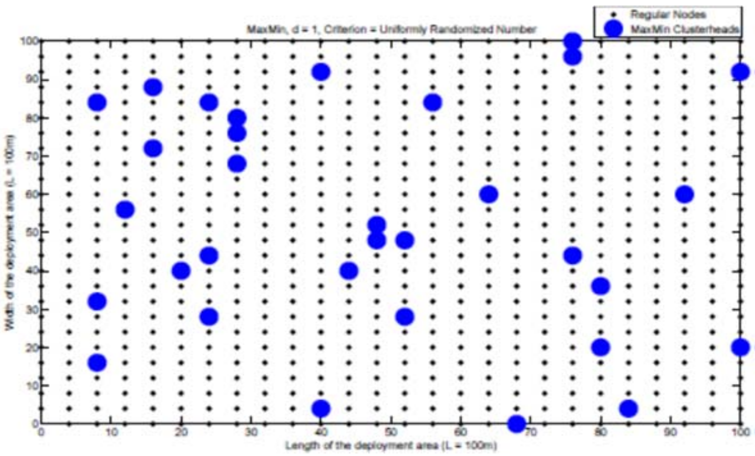

Fig. 7. MaxMin: Average clusterhead locations, Randomized Criterion, d = 1.

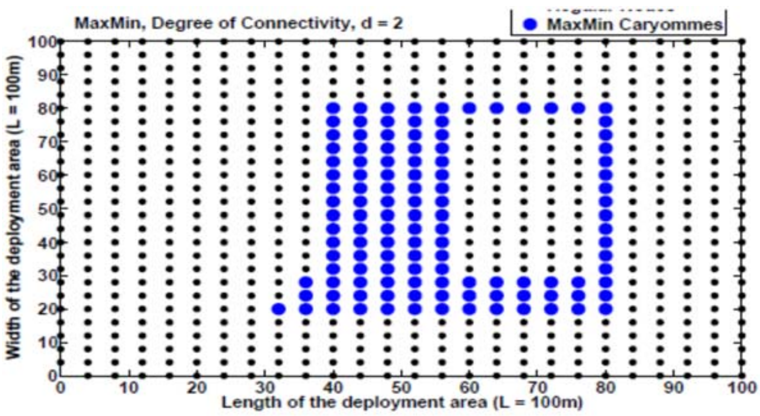

Fig. 8. MaxMin: Average clusterhead locations, degree of connectivity criterion, d = 2.

According to these results, we tend to conclude that MaxMin is not suitable for the grid deployment topology which is by far the most common topology encountered in cold chain monitoring applications.

5. LQI-DCP in the Grid Deployment Topology

The LQI-DCP protocol that we have proposed in [3] is a distributed multihop clustering protocol. LQI-DCP is based on the quality of links in order to swerve locations of the selected clusterheads. In a homogeneous network where all the sensors have the same transmission power, and in the absence of obstacles that can cause high interference, the LQI depends only on the distance separating the nodes. Intended for dense WSNs, its basic idea is to improve the efficiency of the network by caring about to sufficiently swerve the produced clusterheads. LQI-DCP takes place in two rounds. The first round comprises a series of information exchanges making it possible to initialize the algorithm and to preselect the nodes having the greatest criterion value within their neighborhood (i.e. the Preselected Nodes (PN)). Each Preselected Node (PN) designates its emissary nodes among its neighbors (Fig. 9). The emissary nodes allow identifying the neighbors that would be undesirable as clusterhead if the Preselected Node were to be finally elected as clusterhead. These undesirable nodes are called Whipping boy nodes. In the second round, the clusterheads are preferably chosen among the nodes that are not yet belonging to a cluster. A whipping boy node would only become clusterhead as a last resort.

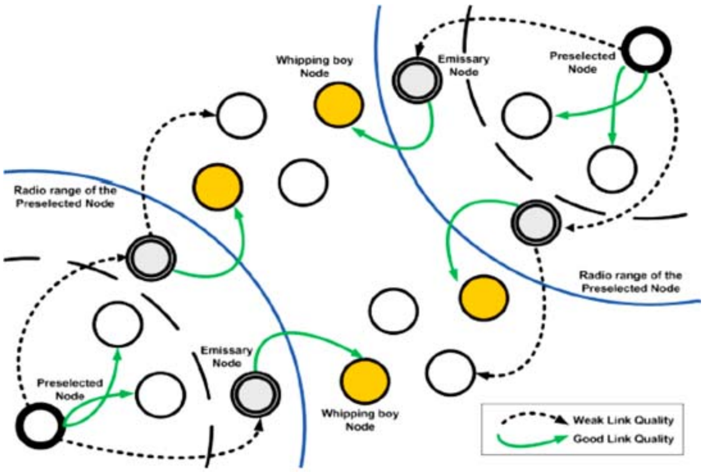

Fig. 9. Preselected, emissary and whipping boy nodes in LQI-DCP.

The first point to note is the redefinition of the notion of the “emissary node” in relation to the definition used in [6], where an additional condition imposed on the emissary node to have a neighbor outside the neighborhood of its “Preselected node” (PN). Removing this condition saves CPU resources and then improves the computation speed of the algorithm.

Then, as we can see in the Figs. 10, 11 and 12 related to the node transition states:

- An emissary node has necessarily a clusterhead.

- A node could be a Whipping boy node if and only if it is not in a cluster or if it is a Preselected Node (PN).

- In the case if a Preselected Node (PN) becomes a Whipping boy node, all the clustered nodes that were attached to it become unclustered.

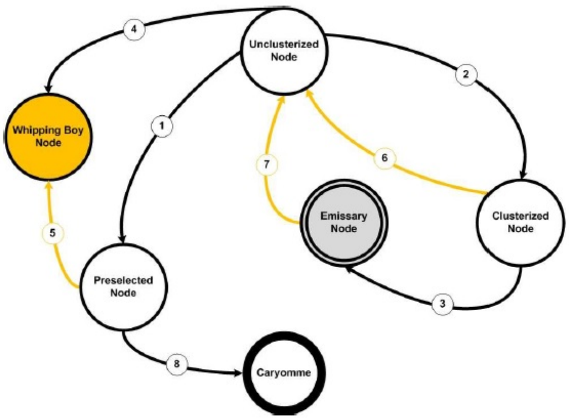

Fig. 10. LQI-DCP: Node transition states in 1st round.

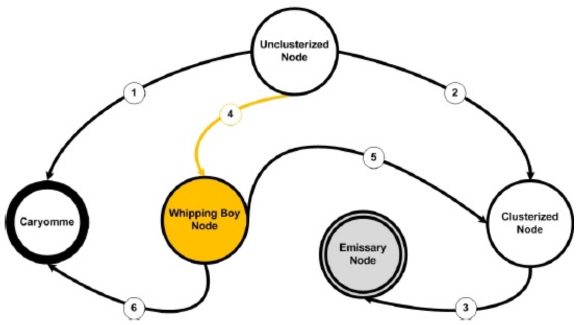

Fig. 11. LQI-DCP: Node transition states in 2nd round.

To overcome the grid topology issue for MaxMin, as we stated in Section IV, one should choose a criterion function of which the values are randomly distributed to the nodes. This helps avoiding a function which is monotonically increasing (or decreasing) along the lines of the grid. Even in this case, LQI-DCP (Figs. 15, 18) is more efficient than MaxMin (Figs. 16, 17) by sufficiently outspreading selected clusterheads.

Conversely our LQI-DCP protocol fully supports the grid deployment topology both for 1-hop and for multihop WSN clustering (Figs. 13, 14, 15, 19).

For LQI-DCP, the results make it possible to distinguish the clusterheads elected after the first round of those who are elected in the second round. The specificity of the Proximity-BS criterion is that it gives only one node elected as a clusterhead in the first round (Fig. 18). This result is explained by the fact that each node has, in its vicinity, at least one other node which is closer to it than the base station; With the exception of the only node of the network which is the closest to the base station. It is precisely this sensor that is the only node to be elected clusterhead in the LQI-DCP first round.

As for the Proximity-BS criterion, the result (Fig. 19) shows that there is only one selected clusterhead in the first round of LQI-DCP when the degree of connectivity is used as selection criterion.

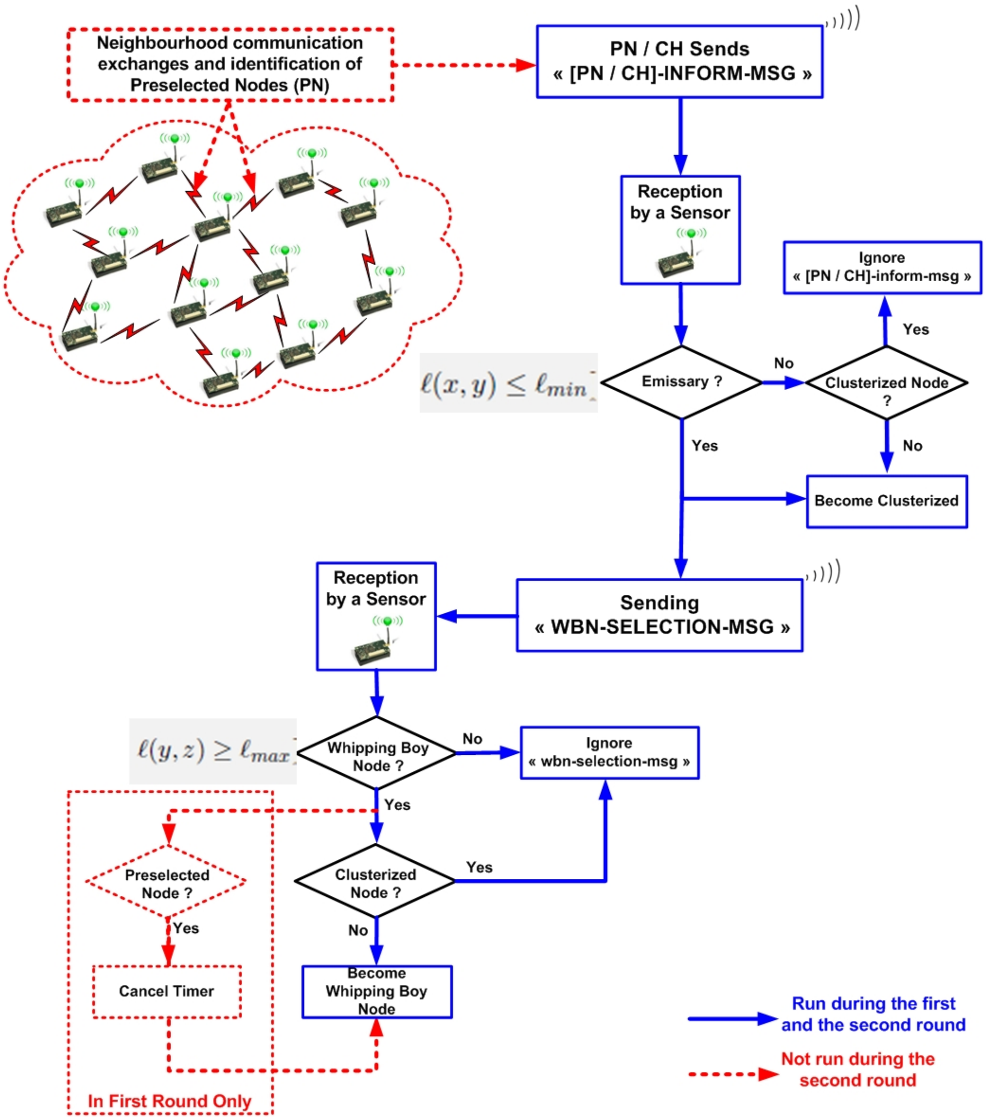

Fig. 12. The LQI-DCP Protocol Flowchart: 1st and 2nd Round. Contrary to the PN-INFORM-MSG, the CH-INFORM-MSG messages are firstly sent during the 2nd Round by the non clusterized nodes and then by the Whipping boy nodes.

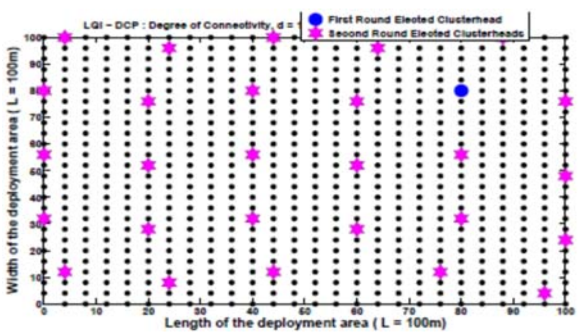

Fig.13. LQI-DCP: Average clusterhead locations, degree of connectivity criterion, d = 1.

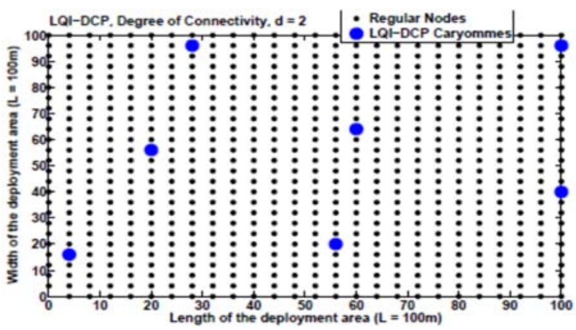

Fig.14. LQI-DCP: Average clusterhead locations, degree of connectivity criterion, d = 2.

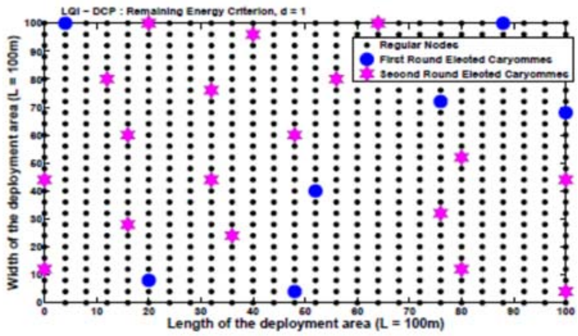

Fig. 15. LQI-DCP: Average clusterhead locations, Remaining Energy criterion, d = 1.

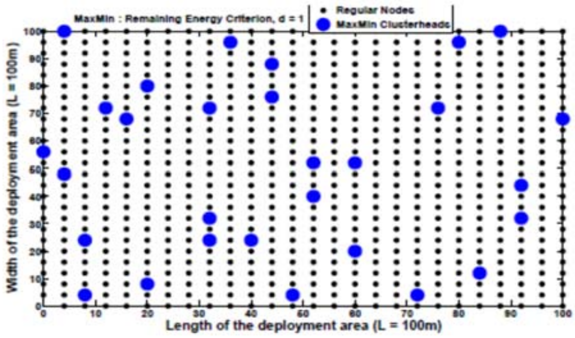

Fig. 16. MaxMin: Average clusterhead locations, Remaining Energy criterion, d = 1.

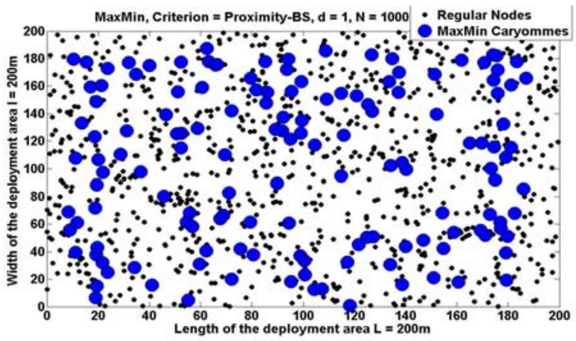

Fig. 17. MaxMin: Average clusterhead locations (Proximity-BS, d=1).

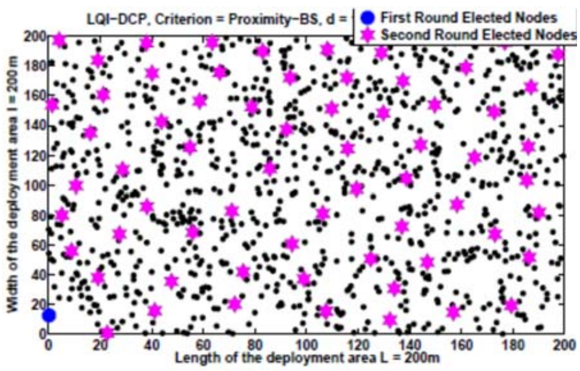

Fig. 18. LQI-DCP: Average clusterhead locations (Proximity-BS, d=1).

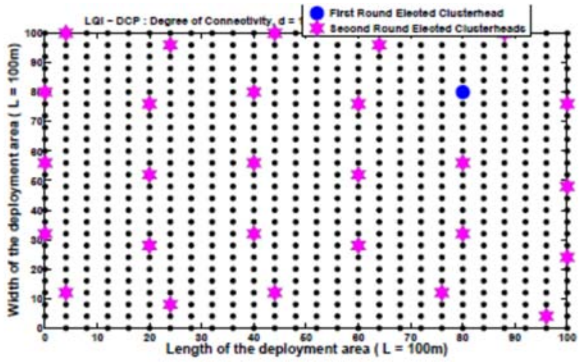

Fig. 19. LQI-DCP in grid topology: Average clusterhead locations (Degree of connectivity, d = 1). For R = 20 m, this result shows that the locations of the clusterheads produced by LQI-DCP is efficient. Moreover, there is only one elected clusterhead after the first round as explained above.

As far as that goes, the explanation is that, in the grid topology, each node has, in its neighborhood, at least another node which has as many as neighbors. The nodes having the same degree of connectivity as per their tie "node IDs" because of the total order relation in *V* defined by the equation:

$$\forall\, x \in V, v(x) = \big(f(x), id(x)\big),$$

Where ***f(x)*** is the criterion function (such as the Proximity-BS, the degree of connectivity) and ***id(x)*** returns the address of the node ***x***. The total ordering in *V* is defined as follows:

$$\forall x, y \in V, v(x) > v(y) \Leftrightarrow \big(f(x) > f(y)\big)$$
$$or\ (f(x) = f(y) and\ id(x) > id(y))$$

So there is finally a single node ***x ϵ V*** in the network that has the highest degree of connectivity that all its neighbors (due to its address value ***id(x)***). This is the node which is logically the only one elected after the first round (Fig. 19).

6. LQI Model for Performance Evaluation Purposes

At each given time ***t***, the LQI value of the link formed by any pair ***(x, y)*** of nodes is calculated by using the ***ℓ(x, y, t)*** function defined below:

$$\ell(x; y, t) = f(x, y, t) * g(x, y),$$
$$f(x, y, t) = 1 - Pr\,[link(x, y, t) = Unreliable],$$
$$g(x, y) = \alpha + \frac{\beta * \log(1 + (\gamma(x, y) - \gamma\min(x)))}{\log(1 + \gamma\max(x))},$$
$$\gamma(x, y) = \frac{1}{d(x,y)},$$
$$\gamma\min(x) = \min_{y \in N1(x)} \gamma(x, y),$$
$$\gamma\max(x) = \max_{y \in N1(x)} \gamma(x, y),$$

where α = 50, β = 255 and ***d(x, y)*** is the distance separating ***y*** from ***x***. ***N1(x)*** is the 1-hop neighborhood of the node ***x***.

In the context of a cold chain monitoring application, the warehouse hosts hundreds of pallets, one upon the other. Each pallet is provided with a temperature sensor. This environment is subjected to some unreliabilities of the wireless links. So, in the formula, ***Pr[link(x,y,t) = Unreliable]*** denotes the probability that the link ***link(x,y,t)*** becomes unreliable at time ***t***. This probability is used in some simulation scenarios, in order to evaluate the behavior of our LQI-DCP protocol with respect to the unreliability feature of the wireless links.

The choice of this model is guided by experimental results shown in [15] and [16], which stated that the LQI decreases when the distance between nodes increases in ZigBee-based WSN.

As we can see, $\ell(x,y,t) \neq \ell(y,x,t)$. Hence, the model allows taking into account asymmetrical aspects of the wireless links.

For moteiv's Tmote Sky [17] sensors equipped with chipcon's CC2420 [18], the LQI values range from 50 to 110. Even so, we stick with the ZigBee standard [19-20] because some manufacturers, such as Sun-SPOT [21] and WiEye [22], are still using the standard LQI values. Then, we use the standard values (i.e., [0, 255]) increased by $\alpha = 50$, instead of those of CC2420. The use of $\alpha = 50$ allows to keep the null value, $\ell(x,y,t) = 0$, only for the two cases where the node ***y*** is not in the transmission range of the node ***x***, or when the $\ell(x,y,t)$ becomes unreliable i.e., ***Pr[link(x,y,t) = Unreliable] = 1***.

This LQI model is only used for simulation purposes, so sensor nodes do not compute these above formulas.

Simulations, using Matlab, are run for a network size ranging from 200 to 4000 nodes. The performance results presented here are obtained by averaging the results for 100 different simulations for the two scenarios (Figs. 20, 21). As for others scenarios 80 different simulations were run. For each simulation, a new random node layout is used.

In all simulation results presented below, $\ell_{max} = 230$ and $\ell_{min} = 70$ as defined in [3].

The MinLQI clusterhead selection criterion is also defined in [2]. For a node, the MinLQI value represents the minimum LQI value beyond a given threshold which is set to 100, in all simulation scenarios.

7. Impacts of the Unreliability Feature of the Wireless Links on LQI-DCP Operations

In the context of a cold chain monitoring application, the warehouse hosts hundreds of pallets, one upon the other. Each pallet is provided with a temperature sensor. This environment is subjected to the unreliability feature of the wireless links. In this section we take into account such a phenomenon. For a sensor S_i, its unreliable links with some neighbors are modeled by the Bernoulli distribution of parameter ***p*** which takes the value "unreliable" with the probability defined as follows:

$$Pr[link(x,y,t) = Unreliable] = 1, \quad if\ \delta(i,j,t) \leq p,$$

where δ(i,j) is a random generated number which is uniformly distributed in]0,1] for each neighbor S_j of the sensor S_i. If ***Pr[link(x,y,t) = Unreliable] = 1***, then at time ***t***, $\ell(x,y,t) = 0$ and the node S_j would not become a whipping boy node related to the emissary node S_i even if S_j is too closely located to S_i.

Before inspecting the impacts of the unreliability feature of the wireless links, it is useful to examine the average ratio of the whipping boy nodes finally elected as clusterheads in the scenario where all links are considered reliable, i.e.:

$$\forall t, \forall x \in V, Pr[link(x,y,t) = Unreliable] = 0, \forall y \in N1(x)$$

Then, the Fig. 20 plots the average number of the whipping boy nodes finally selected as clusterheads divided by the overall number of clusterheads produced by LQI-DCP. For all studied criteria, this ratio is too low. For the proximity with respect to the BS, around ***1 %*** of clusterheads are chosen from the whipping boy nodes. This ratio is between ***1 %*** and ***2,5 %*** for the degree of connectivity criterion and between ***3 %*** and ***4 %*** for the MinLQI criterion.

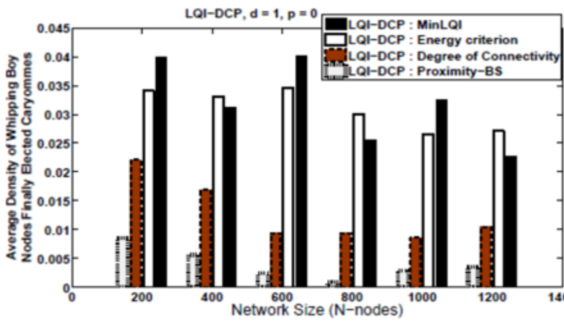

Fig. 20. LQI-DCP: Average density of whipping boy nodes finally selected as clusterheads, d = 1, p = 0.

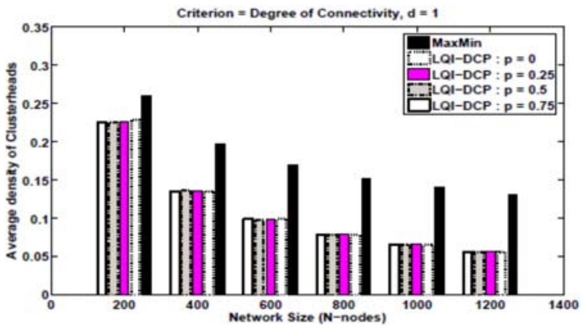

Fig. 21. LQI-DCP: Average density of clusterheads, degree of connectivity criterion, d = 1.

Fig. 21 shows that the unreliability of the wireless links has negligible effects on the average density of clusterheads by comparing results for ***p = 0*** (all links are reliable), ***p = 0.25, p = 0.5 and p = 0.75*** (high unreliability), when the degree of connectivity is used as criterion. Fig. 22 displays the average positions of clusterheads for ***p = 0.75***.

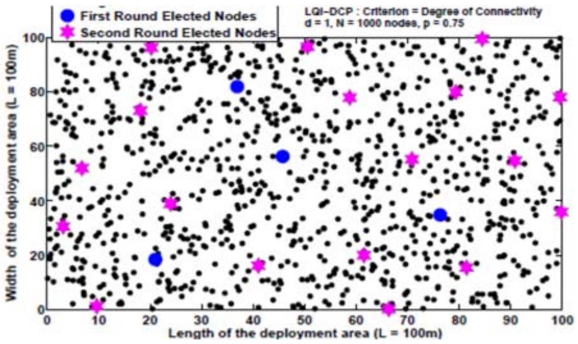

Fig. 22. LQI-DCP: Average clusterhead locations, degree of connectivity criterion, d = 1, p = 0:75.

In these scenarios, no link unreliability is taken into account for the MaxMin clustering scheme. The unreliability feature of the wireless links is only considered for the LQI-DCP clustering protocol.

This result (Fig. 23) is remarkable, because for ***R = 20 m and d=2,*** it means that high unrelibilities of the wireless links ***(p = 0.75)*** do not have negative impacts on LQI-DCP.

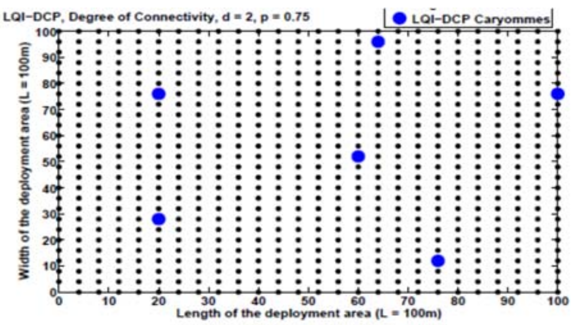

Fig. 23. LQI-DCP: Average clusterhead locations, degree of connectivity criterion, R = 20 m, p = 0:75, multihop clusters d = 2.

For MaxMin protocol, in the results (Fig. 21, 24, 26), the unreliability feature of the wireless links is not taken into account. Then for all scenario in this paper, ***p=0***, for MaxMin protocol. The unreliability feature of the wireless links is taken into consideration only for LQI-DCP.

The Fig. 22, 23, 25 and 27 plot, for LQI-DCP, the average clusterheads location when the WSN is subjected to high unreliability phenomenon of the wireless links, i.e., ***p = 0.75***.

These results show that the unreliability of the wireless links also has negligible effects on the locations of clusterheads selected by LQI-DCP: caryommes are sufficiently outspread. If a link were to be unreliable, the only effect on LQI-DCP is to decrease the number of whipping boy nodes in both first and second round of the LQI-DCP process. As a neighbor of a first round elected node cannot become a clusterhead. Then unreliability of the wireless links has low impact on the LQI-DCP clustering scheme.

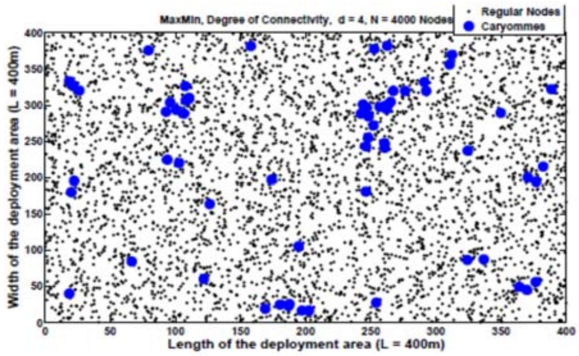

Fig. 24. MaxMin: Average clusterhead locations, degree of connectivity criterion, N = 4000 Nodes, R = 20 m, p = 0, multihop clusters d = 4.

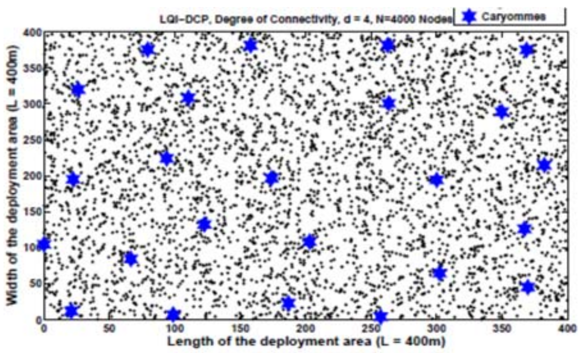

Fig. 25. LQI-DCP: Average clusterhead locations, degree of connectivity criterion, N = 4000 Nodes, R = 20 m, p = 0:75, multihop clusters d = 4.

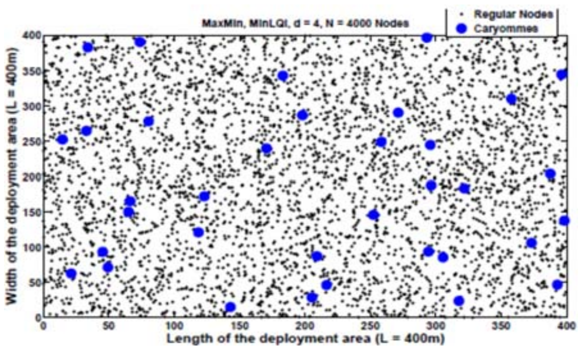

Fig. 26. MaxMin: Average clusterhead locations, MinLQI criterion, N = 4000 Nodes, R = 20 m, p = 0, multihop clustering d = 4.

For explanation, consider the example illustrated in (Fig. 28), in which we suppose that the sensor C_i, although located closely to the preselected node PN, also forms a link of poor quality with PN, i.e., $\ell(PN;C_i) \leq \ell_{min}$. Thus C_i would be an "emissary node" of PN. However, even if C_i has a good link quality with C_j, i.e., $\ell(C_i;C_j) \geq \ell_{max}$, C_j will not become a "whipping boy node", relatively to C_i, because it is already clusterized and attached to PN as clusterhead [3].

In the same example (Fig. 28), the unreliability feature of the wireless links could also affect the quality of the link formed by the emissary node Ei with the sensor BE_i. Which might result in considering BE_ias a non-clusterized regular node which is not a "whipping boy node". However, in a dense WSN, BE_i could have some good links with other emissaries such as E_j or E_k. In this case, BE_i would become a "whipping boy node" (Fig. 28). This property could be less true in cases where the WSN is deployed with a low node density.

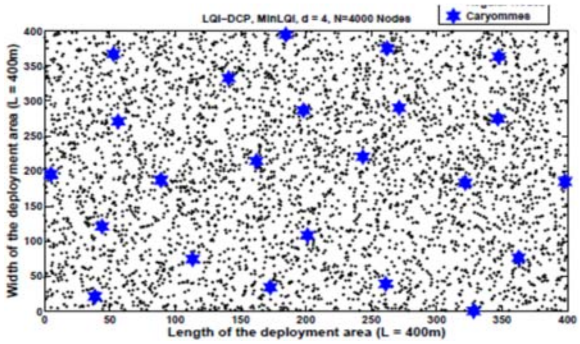

Fig. 27. LQI-DCP: Average clusterhead locations, MinLQI criterion, N = 4000 Nodes, R = 20 m, p = 0:75, multihop clustering d = 4.

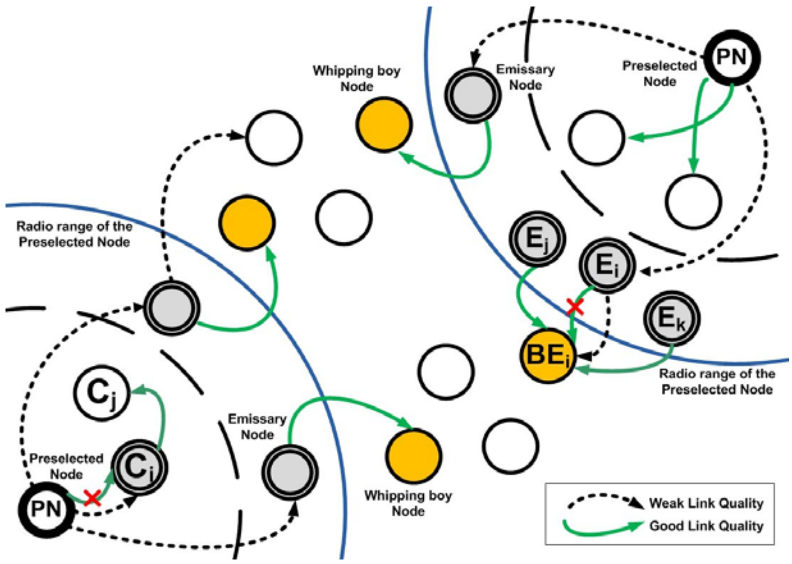

Fig. 28. Stability of LQI-DCP in unreliable link environments.

So, as we can see, in dense wireless sensor networks, our LQI-DCP protocol also supports the unreliability feature of the wireless links.

7. Energy Efficiency

LQI-DCP is designed for dense wireless sensor networks such as cold chain monitoring applications which consist of three main phases: the clustering formation phase, the clusterhead data collection phase and the routing phase (Fig. 29).

Since, the caryommes do not necessary form a connected backbone, all sensors wake up during the routing phase (Fig. 29) in which each caryomme aggregates the received alarms and then sends information towards the BS (Fig. 30). In the routing phase, only caryommes are sources of data packets. Other regular sensors are only participating in the routing effort by retransmitting received data towards the BS. The routing protocol used is the "Link Reliability based Routing Protocol" (L2RP) we have proposed in [23-24].

In the clustering formation phase LQI-DCP is composed of the first and second rounds, whereas MaxMin is composed of its clustering phases (initial, floodmax and floodmin phases), followed by the step of cluster formation with the SNCR mechanism.

The figure (Fig. 31) displays the clustering phase energy consumption for both protocols when the degree of connectivity criterion is used.

In the clustering phase, LQI-DCP provides lower energy consumption compared to MaxMin. This reflects the fact that LQI-DCP is an election in just two rounds, instead of $(2*d + 1)$ rounds for MaxMin. The emissary nodes are designated in the same packet which announces the preselected node, then the cost of the emissary selection mechanism is negligible. However, for the whipping boy node selection, an additional communication is necessary. But as the density of the first round elected nodes is low, and that the overall rate of caryommes is lower for LQI-DCP, this leads to lower energy consumption. It is the same for the data collection and routing phases as shown in [3].

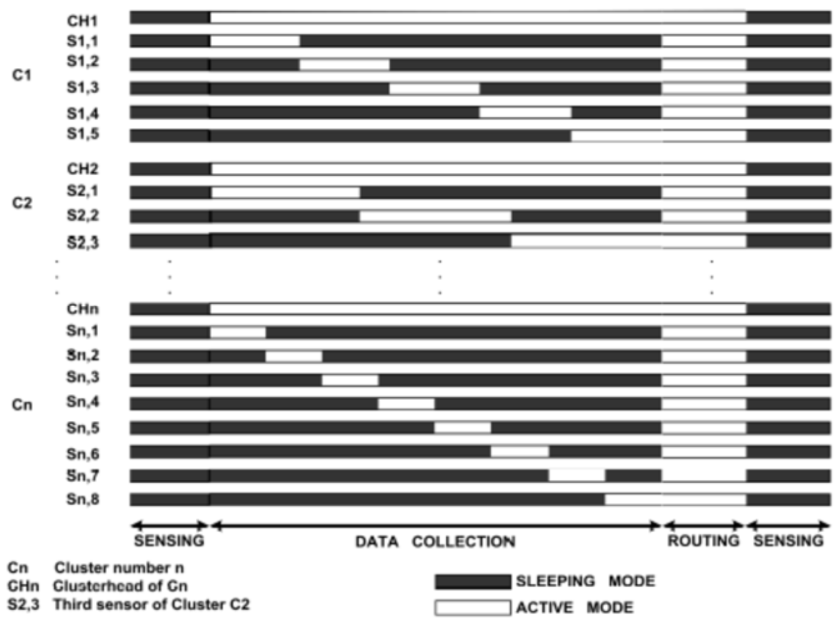

Fig. 29. Active/Sleep mode organization of the WSN [2].

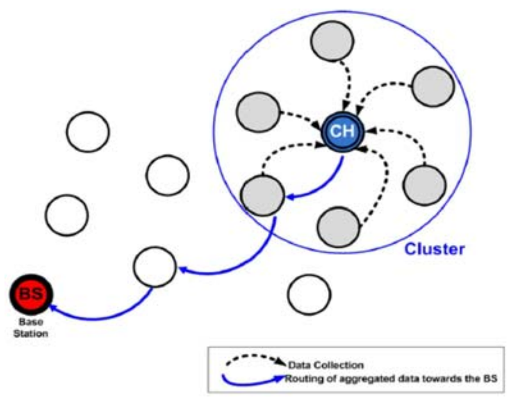

Fig. 30. Clusterhead data collection and routing toward the base station.

The Figs. 32 and 33 show for each protocol the ratio of the energy consumed by each phase during a complete cycle. For MaxMin and the routing phase, for example, it is the average energy consumed during the routing phase (caryommes produced by MaxMin) divided by the overall energy expenditure during one cycle for the same MaxMin protocol. This result depends on the selection criterion. The previous results in [3] have shown that MaxMin is more energy expensive whatever the phase considered and the selection criterion used. However, if one compares the phases within each protocol, the proportion spent by the routing phase (Figs. 32 and 33) is more important in LQI-DCP (60 %) than in MaxMin (55 %).

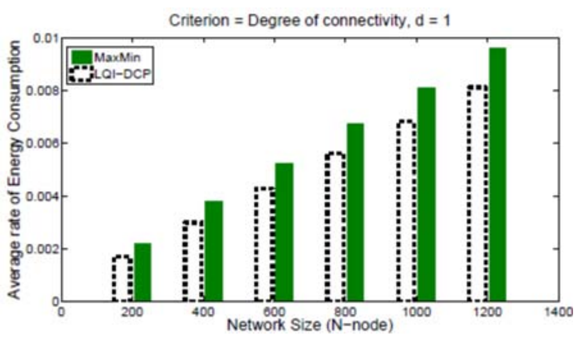

Fig. 31. Average rate of energy consumption (Clustering Phase, d=1).

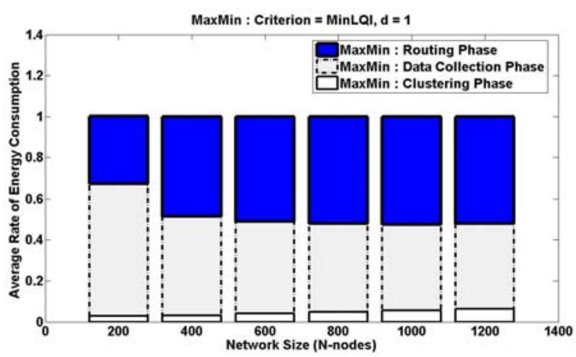

Fig. 32. MaxMin: Average ratio of energy consumption per phase (d=1).

This is due again to the fact that caryommes are better positioned in LQI-DCP than in MaxMin. Indeed, the weak position of caryommes produced by MaxMin has the effect of increasing the energy effort needed to collect data. The caryommes produced by MaxMin more often hear communications which are not intended to them. In LQI-DCP, as caryommes are more evenly distributed geographically, the proportion of energy needed to collect data is lower.

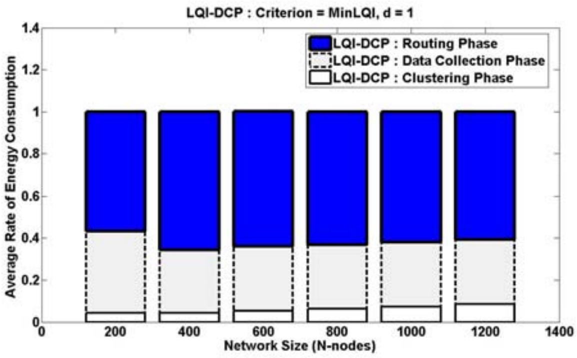

Fig. 33. LQI-DCP: Average ratio of energy consumption per phase (d=1).

7. Conclusions and Future Work

This paper complements our previous contributions in [1-3]. Firstly, there are many WSN deployment strategies. Each of which depends on the nature and the objective for which the application is designed for. However, the deployment strategy and clustering protocol efficiency are so closely bound together that good performance depend on how the protocol follows up the properties of the deployment topology.

Thus, we show how MaxMin is not fully compatible with the prevalent grid deployment topology. So, because of the smoothness of this topology, MaxMin fails with most of the criteria used in clusterhead selection such as "Degree of connectivity", "node id", "MinLQI", and "Proximity-BS". Then, the only way to use MaxMin in a grid deployment topology is to choose a randomized criterion function. However, in doing so, it becomes impossible to choose the most appropriate criteria for a specific application.

Then, we complete the LQI-DCP contribution with some results which show that this protocol fully supports the grid deployment topology. LQI-DCP is also high performance in environments subjected to high unreliabilities of the wireless links. This property is important for a LQI based multihop clustering protocol such LQI-DCP which is more energy efficient than MaxMin. In LQI-DCP, as caryommes are more evenly distributed geographically, the average of overall energy needed for network operations (clustering, data collection and routing processes) is less important than MaxMin.

Finally, it can be noted that security issues and solutions [25] have not been addressed here. Thus, in our future work, we will be interested in the aspects of securing the LQI-DCP protocol while taking care to minimize energy consumption.

Acknowledgements

This research was supported by:

- SAMOVAR CNRS Research Lab – UMR 5157; DeptRéseauxet Services de Télécommunications (RST); TélécomSudParis, Evry, France. I would like to thank Prof. Monique Becker and Prof. Michel Marot of TélécomSudParis. I am more than grateful to them for their help. (http://www.telecom-sudparis.eu/).

- Centre d'ExcellenceenMathématiques, Informatiqueet TIC (CEA-MITIC); UFR Sciences appliquées et de Technologies (UFR SAT), Université Gaston Berger, Saint-Louis, Sénégal. (http://www.ceamitic.sn/).

References

[1]. C. Diallo, Effects of the WSN deployment environment on MaxMin and LQI-DCP multihop clustering protocols, in *Proceedings of the 2nd International Conference on Advances in Sensors, Actuators, Metering and Sensing (ALLSENSORS'17),* Nice, France, March 2017, pp. 24-29.

[2]. C. Diallo, M. Marot, M. Becker, Single-node cluster reduction in WSN and energy-efficiency during cluster formation, in *Proceedings of the 9th IEEE/IFIP Annual Mediterranean Ad Hoc Networking Workshop, Med-Hoc-Net*, Juan-Les-Pins, France, June 2010, pp. 1-10.

[3]. C. Diallo, M. Marot, M. Becker, A distributed link quality based d-clustering protocol for dense ZigBee sensor networks, *in Proceedings of the Third IFIP/IEEE Wireless Days International Conference, (WD'10)*, Venice, Italy, October 2010, pp. 1-6.

[4]. N. Assad, Optimisation du déploiement des réseaux de capteurs sans fil: couverture de la zone de surveillance et connectivité du réseaudansune application de détectiond'intrusion, PhD Dissertation,*Faculté des Sciences de Rabat, Université Mohammed V Rabat*, 2015.

[5]. C. Diallo, Techniques d'amélioration du routage et de la formation des clusters multi-sautsdans les réseaux de capteurssans fil, PhD Dissertation, *TélécomSudParis,* 2010.

[6]. C. Diallo, M. Marot, M. Becker, Using LQI to improve clusterhead locations in dense ZigBee based wireless sensor networks, in *Proceedings of the 6th IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob'10),* Niagara Falls, Canada, October 2010, pp. 137-143.

[7]. A. D. de Clauzade de Mazieux, M. Marot, M. Becker, Correction, generalisation and validation of the "Max-Min d-cluster heuristic", in *Proceedings of the IFIP/TC6/LNCS NETWORKING,* Atlanta, USA, May 2007.

[8]. A. Amis, R. Prakash, T. Vuong, D. Huynh, Max-Min d-cluster formation in wireless ad hoc networks, in *Proceedings of the 9thIEEE Annual Joint Conference on Computer and Communications Societies*, Vol. 1, 2000, pp. 32-49.
[9]. M. T. Sow, C. Diallo, Energy over-consumption induced by securing network operations, in *Proceedings of the 2nd IEEE International Conference on Frontiers of Sensors Technologies, IEEE-ICFST'17*, Shenzhen, China, April 2017, pp. 154-160.
[10]. A. Makhoul, Réseaux de capteurs: localisation, couverture et fusion de données, PhD Dissertation, *l'Université de Franche-Comté,* 2008.
[11]. A. Delye, Etude théorique des clusters multi-sautsdans les réseaux de capteurs sans fils, in Thèse de Doctorat, *Université(Paris VI),* France, 2007.
[12]. M. Marot, Conception etanalyse de méthodesd'agrégation et multiniveauxdans les réseaux, in Habilitation à Diriger des Recherches (HDR), *Université Pierre et Marie Curie (Paris VI),* 2009.
[13]. D. Baker, A. Ephremides, The architectural organization of a mobile radio network via a distributed algorithm, in *IEEE Transactions on Communications,* Vol. 29, No. 11, 1981, pp. 1694-1701.
[14]. A. Ephremides, J. Wieselthier, D. Baker, A design concept for reliable mobile radio networks with frequency hopping signaling, in *Proceedings of the IEEE,* Vol. 75, No. 1, 1987, pp. 56-73.
[15]. J. Blumenthal, R. Grossmann, F. Golatowski, D. Timmermann, Weighted centroid localization in ZigBee-based sensor networks, in *Proceedings of the IEEE International Symposium on Intelligent Signal Processing (WISP'07),* 2007, pp. 1-6.
[16]. M. Becker, A.-L. Beylot, R. Dhaou, A. Gupta, R. Kacimi, M. Marot, Experimental study: Link quality and deployment issues in wireless sensor networks, in *Proceedings of the NETWORKING'09, LNCS,* 5550, Aachen, Germany, 2009, pp. 14-25.
[17]. Tmote Sky datasheet, http://www.moteiv.com/products/docs/tmote-skydatasheet.pdf
[18]. C. Radio, http://www.chipcon.com
[19]. Wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (WPANs), IEEE Standard 802.15.4-2006, *IEEE Computer Society,* 2006.
[20]. ZigBee specification v1, *ZigBee*, June 2005.
[21]. S. S. World, http://www.sunspotworld.com.
[22]. E. W. S. Board, http://www.easysen.com/wieye.htm
[23]. C. Diallo, M. Marot, M. Becker, Link quality and local load balancing routing mechanisms in wireless sensor networks, in *Proceedings of the 6th Advanced International Conference on Telecommunications, (AICT'10),* Barcelona, Spain, May 2010.
[24]. C. Diallo, M. Marot, M. Becker, Efficiency benefits through load-balancing with link reliability based routing in WSNs, *International Journal on Advances in Networks and Services*, Vol. 3,No. 3-4, Feb. 2011.
[25]. C. Diallo, A. Sawaré, M. T. Sow, Security issues and solutions in wireless sensor networks, *International Journal of Computer Science and Information Security (IJCSIS),* Vol. 15, No. 3, March 2017.
