Effects of the WSN Deployment Environment on MaxMin and LQI-DCP Multihop Clustering Protocols

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***Abstract*—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. In [1] we improve 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 high unreliable link environments. Performance evaluation results also show that LQI-DCP fully supports the grid deployment topology.**

***Keywords*–Wireless Sensor Network; Multihop Clustering; LQI; MaxMin; LQI-DCP.**

I. Introduction and backgrounds

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.

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 [2] in such a topology.

In [1] and [3], we show how it is important to sufficiently outspread clusterhead in oder 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 [2][4], has the drawback of not taking into account this problem. In order to solve this issue, we have proposed LQI-DCP in [5]. LQI-DCP is an 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.

Previous works [1][2][4] present details on MaxMin, whereas LQI-DCP is described in [5]. All clusterhead selection criteria used in this paper are defined in [1][5]. As in [1][5] we indifferently use caryomme(s) or clusterhead(s).

To carry out our work, this paper is organized as follows: the MaxMin Pathological Case is described in tne next section. Consequently, we explain, in the third section, why MaxMin does not support the grid deployment topology. Then, in the fourth section, we present how LQI-DCP is well adapted for the grid deployment topology. Finally, the last two parts present performance results pertaining to the LQI-DCP protocol when one takes into account the unreliability feature of the wireless links.

II. The MaxMin Pathological Case

Given the similarities with Linked Cluster Algorithm (LCA) [6] and LCA2 [7], MaxMin naturally inherits the same pathological case. Thus, in the original paper [4] 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 (see Figure 1) and the argument as they were stated in [4] : *"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 Figure 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."*

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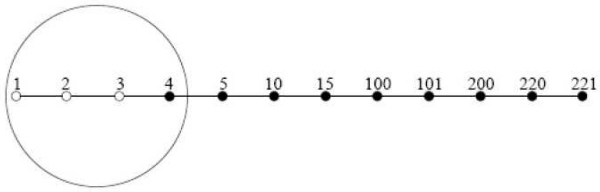

Figure 1. Worse case performance scenario for MaxMin [4]

In the next section, we will show how this pathological case has negative impacts on the grid deployment topology. Indeed, the authors of [4] 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.

III. 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 Figure 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 pitch λ. Then, the coordinates $x(i)$ and $y(i)$ of the i^{th} node $i \in [\![1, N]\!]$ are obtained as follows:
$n = \lfloor \frac{L}{\lambda} \rfloor$, $m = \lfloor \frac{l}{\lambda} \rfloor$, $N = ((n+1) * (m+1)) - 1$, where $\lfloor \frac{L}{\lambda} \rfloor$ denotes the integer part of $\frac{L}{\lambda}$
$x(i) = \lambda * \lfloor \frac{i}{m+1} \rfloor$
$y(i) = \lambda * i \bmod (n+1)$

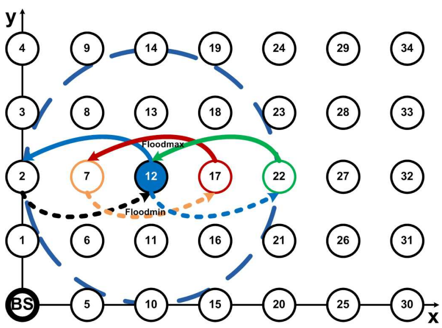

Figure 2. *MaxMin incompatibility with the grid deployment topology*

If we assume that all nodes have the same transmission range $R = 2 * \lambda$, then by running MaxMin algorithm with the parameter $d = 1$ and the function criteria $f(x) = id(x)$ for the WSN example in (Figure 2):

- During **floodmax** phase, the node 2 receives the value 12 from 12^{th} node.
- Next, the node 12 receives this value 12 from 2^{th} node during the **floodmin** phase.
- Accordingly, the 12^{th} node is selected as clusterhead.
- As far as that goes, all the i^{th} nodes, $i \in [\![10, 30]\!]$ (Figure 2), are selected as clusterhead.
- More generally, it's easy to show that all the i^{th} nodes $i \in [\![2(m+1), N]\!]$ are selected as clusterhead by MaxMin.

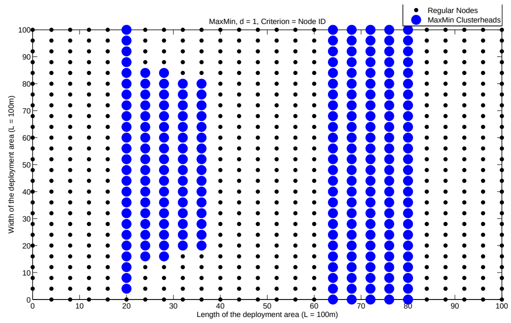

Figure 3. MaxMin: Average clusterhead locations, Node ID criterion, $d = 1$

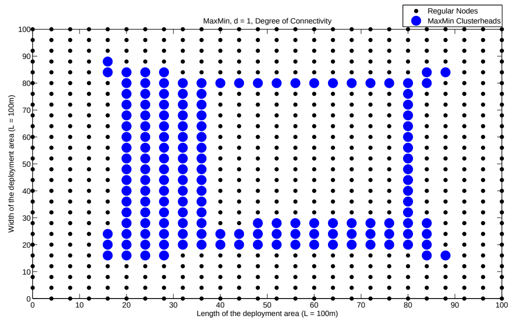

Figure 4. MaxMin: Average clusterhead locations, Degree of Connectivity criterion, $d = 1$

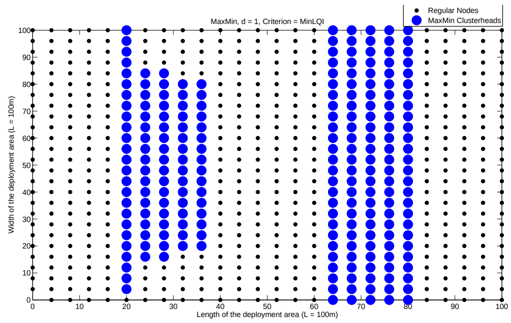

Figure 5. MaxMin: Average clusterhead locations, MinLQI criterion, $d = 1$

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 critera 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) [1] leads to the following results for criteria: "Node id" (Figure 3), "Degree of connectivity" (Figure 4), and "MinLQI" (Figure 5). These results are explained by the neighbourhood relationship (transmission range) between the selected clusterheads. So, we obtain a series of clusterheads located in adjacent columns which are periodically seperated by adjacent columns composed of regular nodes (Figure 5).

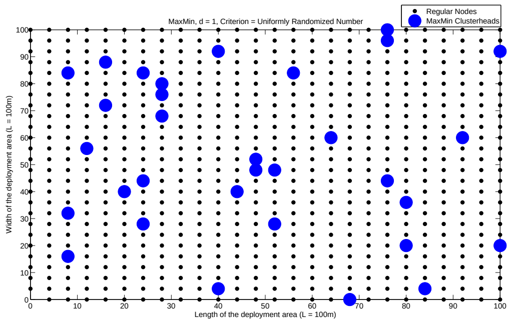

Figure 6. MaxMin: Average clusterhead locations, Randomized Criterion, $d = 1$

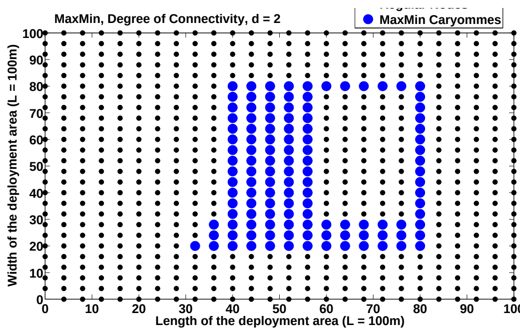

Figure 7. *MaxMin: Average clusterhead locations, degree of connectivity criterion,* $d = 2$

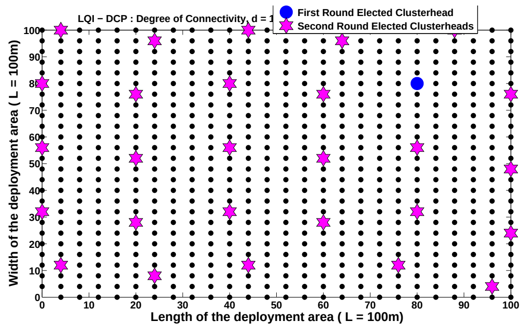

Figure 8. *LQI-DCP: Average clusterhead locations, degree of connectivity criterion,* $d = 1$

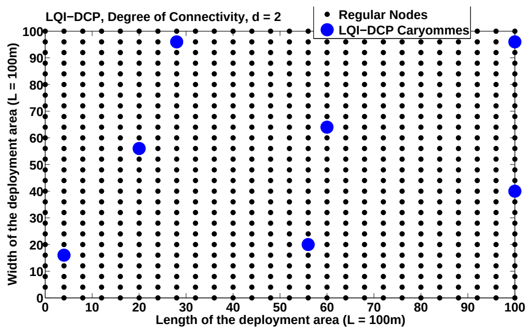

Figure 9. *LQI-DCP: Average clusterhead locations, degree of connectivity criterion,* $d = 2$

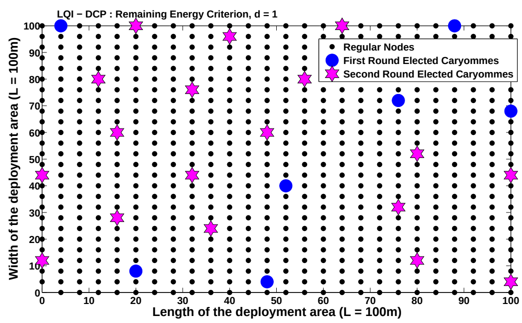

Figure 10. *LQI-DCP: Average clusterhead locations, Remaining Energy Criterion,* $d = 1$

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 (Figure 6) but also has the disadvantage of leading to unpredictable results. Indeed, the benefits 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. Figure 6 shows the location of caryommes obtained for a randomized function criteria. 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 [1].

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.

The MaxMin pathological case is also a big drawback for multihop clusters, $d \geq 2$, as shown in Figure 7.

To overcome this problem with MaxMin, as we stated in Section III, 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 (Figure 10) is more efficient than MaxMin (Figure 11) 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 (Figures 8 and 9).

IV. 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 $\ell(x, y, t)$ function defined below:

$$\ell(x, y, t) = f(x, y, t) * g(x, y) \tag{1}$$

$$f(x, y, t) = 1 - Pr\left[\ell ink(x, y, t) = Unreliable\right] \tag{2}$$

$$g(x, y) = \alpha + \frac{\beta * \log(1 + (\gamma(x, y) - \gamma_{min}(x)))}{\log(1 + \gamma_{max}(x))} \tag{3}$$

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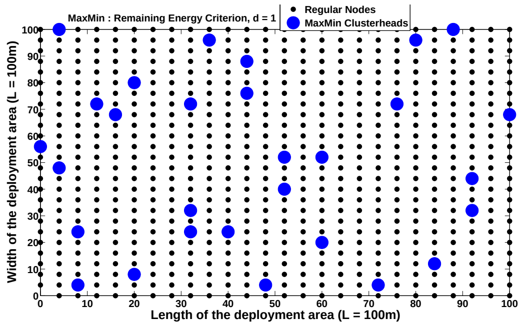

Figure 11. *MaxMin: Average clusterhead locations, Remaining Energy Criterion,* $d = 1$

$$\gamma_(x, y) = \frac{1}{d(x, y)} \quad (4)$$

$$\gamma_{min}(x) = \min_{y \in \mathcal{N}_1(x)} \gamma(x, y) \quad (5)$$

$$\gamma_{max}(x) = \max_{y \in \mathcal{N}_1(x)} \gamma(x, y) \quad (6)$$

where $\alpha = 50$, $\beta = 255$ and $d(x, y)$ is the distance separating y from x.

In the context of a cold chain monitoring application, the warehouse hosts hundreds of pallets, one upon the other. Each pallets is provided with a temperature sensor. This environment is subjected to some unreliabilities of the wireless links. So, in the formula (2), $Pr\,[\ell ink(x, y, t) = Unreliable]$ denotes the probability that the link $\ell ink(x, y, t)$ 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 unrelibility aspect of the wireless links.

The choice of this model, formula (3), is guided by experimental results shown in [8] and [9], which stated that the LQI decreases when the distance between nodes increases in Zigbee-based WSN.

As we can see, $\ell(x, y, t) \neq \ell(y, x, t)$, because of the formulas (5) and (6). Hence, the model allows to take into account asymetrical aspects of the wireless links.

For moteiv′s Tmote Sky [10] sensors equipped with chipcon′s CC2420 [11], the LQI values range from 50 to 110. Even so, we stick with the ZigBee standard [12],[13] because some manufacturers, such as Sun-SPOT [14] and WiEye [15], 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 $\ell ink(x, y, t)$ becomes unreliable i.e., $Pr\,[\ell ink(x, y, t) = Unreliable] = 1$.

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 (Figures 12 and 13). 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 [5]. The MinLQI clusterhead selection criterion is also defined in [1]. For a node, the MinLQI value represents the minimum LQI value beyond a given threshold which is set to 100, in all simulation scenarios.

V. 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 pallets is provided with a temperature sensor. This environment is subjected to some unreliabilities of 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:

$$Pr\,[\ell ink(i, j, t) = Unreliable] = 1\ ,\ if\ \delta(i, j, t) \leq p \quad (7)$$

where $\delta(i, j)$ is a random generated number which is uniformly distributed in $]0, 1]$ for each neighbor S_j of the sensor S_i. If $Pr\,[\ell ink(i, j, t) = Unreliable] = 1$, then at time t, $\ell(i, j, t) = 0$ 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.

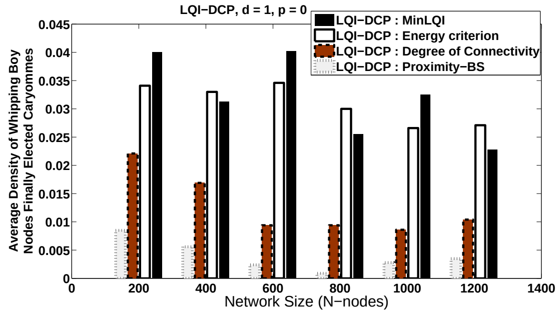

Figure 12. *LQI-DCP: Average density of whipping boy nodes finally selected as clusterheads,* $d = 1$, $p = 0$

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.:

$\forall t,\ \forall x \in V,\ Pr\,[\ell ink(x, y, t) = Unreliable] = 0\ , \forall y \in \mathcal{N}_1(x)$. (8)

Then Figure 12 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 choosen 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.

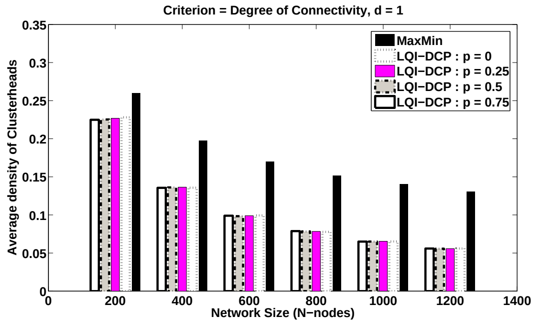

Figure 13. *LQI-DCP: Average density of clusterheads, degree of connectivity criterion,* $d = 1$

Figure 13 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. Figure 14 displays the average positions of clusterheads for $p = 0.75$. In these scenarios, no unreliability is taken into account for the MaxMin clustering scheme. Wireless link unrelibilities are only considered for the LQI-DCP clustering scheme.

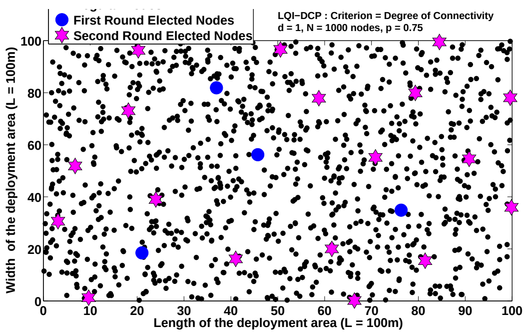

Figure 14. *LQI-DCP: Average clusterhead locations, degree of connectivity criterion,* $d = 1$, $p = 0.75$

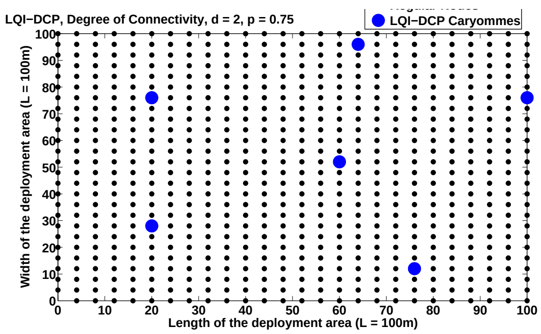

Figure 15. *LQI-DCP: Average clusterhead locations, degree of connectivity criterion,* $R = 20m$, $p = 0.75$, *multihop clusters* $d = 2$.

This result (Figure 15) is remarkable, because for $R = 20m$ and $d = 2$, it means that high unrelibilities of the wireless links $(p = 0.75)$ do not have negative impacts on LQI-DCP.

For MaxMin protocol, in the results (Figures 13, 16 and 18), the unreliability feature of the wireless links is not taken

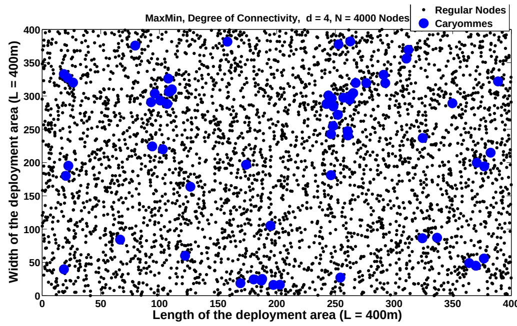

Figure 16. *MaxMin: Average clusterhead locations, degree of connectivity criterion, N = 4000 Nodes,* $R = 20m$, $p = 0$, *multihop clusters* $d = 4$.

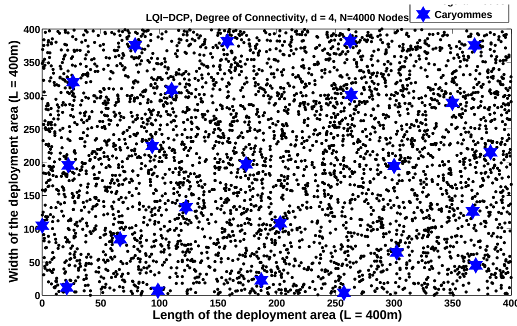

Figure 17. *LQI-DCP: Average clusterhead locations, degree of connectivity criterion, N = 4000 Nodes,* $R = 20m$, $p = 0.75$, *multihop clusters* $d = 4$.

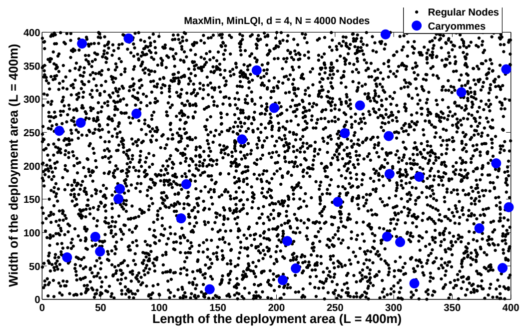

Figure 18. *MaxMin: Average clusterhead locations, MinLQI criterion, N = 4000 Nodes,* $R = 20m$, $p = 0$, *multihop clustering* $d = 4$.

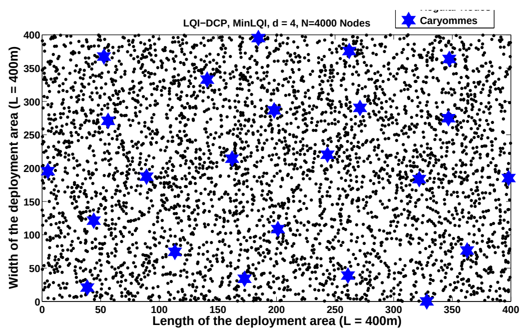

Figure 19. *LQI-DCP: Average clusterhead locations, MinLQI criterion, N = 4000 Nodes,* $R = 20m$, $p = 0.75$, *multihop clustering* $d = 4$.

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.

Figures 14, 15, 17 and 19 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 can not become a clusterhead. Then unreliability of the wireless links has low impact on the LQI-DCP clustering scheme.

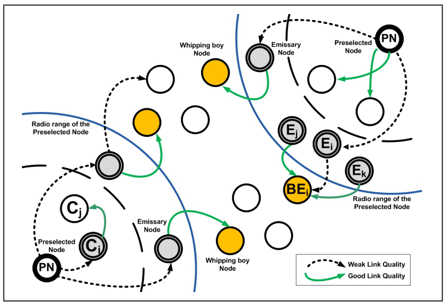

Figure 20. *Stability of LQI-DCP in unreliable link environments*

For explanation, consider the example illustrated in Figure 20, 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 [5].

In the same example (Figure 20), the unreliability of the wireless links could also affect the quality of the link formed by the emissary node E_i with the sensor BE_i. Which might result in considering BE_i as 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" (Figure 20). This property could be less true in cases where the WSN is deployed with a low node density.

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

VI. Conclusion and Future Work

This paper complements our previous contributions [1] and [5]. Firstly, it shows 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 radomized criterion function. However, in doing so, it becomes impossible to choose the most appropriate criteria for a specific application.

Secondly, we complete the LQI-DCP contribution with some results which show that this protocol fully supports the grid deployment topology. LQI-DCP is also performant in environments subjected to high unreliabilities of the wireless links. This property is important for a LQI based multihop clustering protocol such LQI-DCP.

Finally, it can be noted that the issue of security has 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.

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References

[1] C. Diallo, M. Marot, and M. Becker, “Single-node cluster reduction in wsn and energy-efficiency during cluster formation,” in Proc. of the 9th IFIP Annual Mediterranean Ad Hoc Networking Workshop, Med-Hoc-Net 2010, IEEE Communications Society, Juan-Les-Pins, France, June. 2010.

[2] A. D. de Clauzade de Mazieux, M. Marot, and M. Becker, “Correction, generalisation and validation of the "max-min d-cluster heuristic",” in Proc. of IFIP/TC6/LNCS NETWORKING, Atlanta, USA, May 2007.

[3] C. Diallo, M. Marot, and M. Becker, “Using lqi to improve clusterhead locations in dense zigbee based wireless sensor networks,” in Proc. of the 6th IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob 2010), Niagara Falls, Canada, October 2010.

[4] A. Amis, R. Prakash, T. Vuong, and D. Huynh, “Max-min d-cluster formation in wireless ad hoc networks,” in 9th Annual Joint Conference of the IEEE Computer and Communications Societies, 2000.

[5] C. Diallo, M. Marot, and M. Becker, “A distributed link quality based d-clustering protocol for dense zigbee sensor networks,” in Proc. of the third IFIP/IEEE Wireless Days International Conference, WD 2010, Venice, Italy, October 2010.

[6] D. Baker and A. Ephremides, “The architectural organization of a mobile radio network via a distributed algorithm,” in IEEE Transactions on Communications, Vol. COM-29, No 11, pp. 1694-1701, Nov. 1981.

[7] A. Ephremides, J. Wieselthier, and D. Baker, “A design concept for reliable mobile radio networks with frequency hopping signaling,” in Proceedings of IEEE, Vol. 75(1), pp. 56-73, 1987.

[8] J. Blumenthal, R. Grossmann, F. Golatowski, and D. Timmermann, “Weighted centroid localization in zigbee-based sensor networks,” in IEEE International Symposium on Intelligent Signal Processing, WISP'07, 2007.

[9] M. Becker, A.-L. Beylot, R. Dhaou, A. Gupta, R. Kacimi, and M. Marot, “Experimental study: Link quality and deployment issues in wireless sensor networks,” in Proc. NETWORKING'09, LNCS 5550, NETWORKING , Aachen, Germany, 2009, pp. 14–25.

[10] Tmote Sky datasheet., http://www.moteiv.com/products/docs/tmote-sky-datasheet.pdf.

[11] C. Radio, “http://www.chipcon.com,” Last access, Mar. 2010.

[12] I. S. 802.15.4-2006, “Wireless medium access control (mac) and physical layer (phy) specifications for low-rate wireless personal area networks (wpans),” in IEEE Computer Society, 2006.

[13] Z. specification, “Zigbee specification v1,” June 2005.

[14] S. S. World, “http://www.sunspotworld.com,” Last access, Mar. 2010.

[15] E. W. S. Board, “http://www.easysen.com/wieye.htm,” Last access, Mar. 2010.

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