LQI-DCP: A LQI based Multihop Clustering Protocol for Wireless Sensor Networks

Chérif Diallo, Michel Marot, Monique Becker

SAMOVAR CNRS Research Lab – UMR 5157; Dept Réseaux et Services de Télécommunications (RST)
Institut TELECOM; TELECOM SudParis; 9, Rue Charles Fourier – 91011 Evry CEDEX, France
Email:{cherif.diallo, michel.marot, monique.becker}@telecom-sudparis.eu

***Abstract*—The Link Quality Indicator (LQI) is defined in the 802.15.4 standard, but its context of use is not specified in this standard. Some works on the LQI, few of which are field experiments, have shown that the LQI decreases as the distance increases. In WSN, it is not often desirable to use the GPS technology. Indeed, the use of GPS is expensive and may reduce the overall network performance. Moreover, indoor reception of the GPS signal is not possible. However, in cluster formation, it is quite important to sufficiently outspread the clusterheads (or caryommes) in order to improve the network efficiency. Therefore we propose a LQI based d-clustering protocol (LQI-DCP) which produces clusters of which each clusterhead has a better positioning regarding the locations of other clusterheads. Simulation results show that the caryommes 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 remains still at less than d-hops from a caryomme.**

***Index Terms*—WSN Clustering; LQI; LQI-DCP; MaxMin; Clusterhead locations; Energy-efficiency.**

I. Introduction

In the Zigbee standard [1],[2], the LQI measurement is defined as a characterization of the strength and/or quality reception of a packet. The use of the LQI result by the network or the application layers is not specified in [1],[2]. The LQI measurement is performed for each received packet, and the result is reported to the MAC sublayer as an integer ranging from 0 to 255. The minimum and maximum LQI values (0 and 255) are associated with the lowest and the highest quality IEEE 802.15.4 reception detectable by the receiver, and the LQI values in between are distributed between these two limits [1],[2]. The proposed algorithm is a distributed LQI based clustering protocol (LQI-DCP) which runs in two rounds. LQI-DCP is built such that, in the first round, the preselected nodes rely on some of their neighbors (called the emissary nodes) to designate undesirable nodes (called whipping boy nodes) which would be only elected in last resort. To make their decisions, the preselected nodes and the emissary nodes use the quality of the links they form with its respective neighbors. LQI is used in order to take into account the distance separating nodes. As the GPS technology is expensive and is high energy consumer, it is not often desirable to add GPS futures in the WSN. Furthermore, in some applications, it is not a requirement to precisely determine the node locations. In such application it is only sufficient to have an idea on the remoteness of some nodes with respect to any given sensor. Thus, in the proposed LQI-DCP, the LQI value is used in such a way that the nodes which would have negative impacts on the network performance could only become clusterhead in last resort. LQI-DCP also forms d-clusters where each node within a cluster is at most d hops away from its clusterhead. In a cold chain monitoring application, due to the size of a warehouse which hosts a large number of pallets, provided each with a temperature sensor, the 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 features and then reduce the computation complexity of data gathering and routing protocols. Applying the LQI-DCP protocol to a cold chain monitoring application, we show how it improves the network performance by sufficiently outspreading the produced caryommes. In this application LQI-DCP is used to select the caryommes which manage their respective clusters upon a TDMA based organization. Regular sensors send alarms to their respective caryommes which aggregate them and then forward data towards the BS using the "Link Reliability based Routing Protocol" (L2RP) we have proposed in [3]. L2RP is run with the weighted round robin load balancing mechanism using the "MinLQI" metric. MaxMin [4] is an effective heuristic for d-cluster formation in wireless sensor networks. This protocol has recently been corrected, generalized and validated in [5],[6]. Then we have optimized MaxMin by providing a simple mechanism to reduce the single-node clusters and then increase the energy efficiency [7]. The proposed LQI-DCP protocol is compared to this optimized form of MaxMin. The rest of this paper is organized as follows. After an overview of the related works in the next part, the next one gives an understanding of the proposed LQI-DCP algorithm. In the fourth part, we present the clusterhead selection criteria used to evaluate the protocol. The last section presents simulation results pertaining to a cold chain monitoring application in which LQI-DCP is compared to the MaxMin heuristic.

II. State of the Art

In Zigbee [1],[2] a cluster-tree topology is provided with the standard 802.15.4 std. A ZigBee system consists of several components. The most basic is the device. A device can be a full-function device (FFD) or reduced-function device (RFD). A network shall include at least one FFD, operating as the PAN coordinator. The PAN coordinator forms the first cluster by establishing itself as the clusterhead (CH) with a cluster identifier of zero, choosing an unused PAN identifier, and broadcasting beacon frames to neighboring devices. A candidate device receiving a beacon frame may request to join the network at the CH. If the PAN coordinator permits the device to join, it will add this new device as a child device in its neighbor list. This cluster-tree topology is well suited to heterogeneous networks but is not fully scalable for large homogeneous WSN. Few papers concern LQI based clustering protocols for WSN. In [8], authors propose a link-state clustering algorithm (LSCA) for both homogeneous and heterogeneous large scale wireless sensor networks. Based on the link state of the radio channel, LSCA forms clusters of which clusterheads form a backbone for data routing. The LEACH [9] algorithm for selecting clusterheads is a probabilistic method which produces clusters with a large variation of link distances and uneven energy consumption during the data transmission phase. To address this issue, a RF signal strength algorithm based on link quality is presented in [10]. In this distributed algorithm [10], nodes attempt to reduce the overall energy required for transmission in addition to forming favourable clusters based on Received Signal Strength indication (RSSI) density and quality. These papers do not take into account multihop clustering aspects. Multihop clustering algorithms address two main challenges: first, the question arises how to optimally choose the caryommes with respect to their locations and, secondly, how to construct the parental relationship between regular nodes and their caryommes in such a way that any common sensor can reach its clusterhead within k hops, that is to say, how to construct an optimally independent k-dominating set. Unfortunately, finding such a set is an NP-complete problem [4], so some heuristics have been proposed. In [11], Dai and Wu proposed three algorithms to build k-dominating sets which are also k-connected. One method is to compare sensor values (criteria) such as node ID, "remaining energy level", weight, etc. (cf. KHOPCA in [12], CABCF in [13], MaxMin in [4]). It is possible that two nodes have the same criterion value. Then, in [14] and [5], the authors propose to consider the pair composed by the degree of connectivity of the node and its address. Some works ([15],[16],[17],[18],[19]) introduced the notion of single-node clusters as a performance criterion for evaluating clustering protocols, whithout showing why single-node clusters are not a desirable feature in WSN. In [7] we show how much single-node clusters could have negative impacts on the network efficiency. MaxMin [4] is an effective heuristic for d-cluster formation in wireless sensor networks. This protocol has recently been corrected, generalized and validated in [5],[6]. Then in [7] we provide a simple mechanism to reduce the single-node cluster phenomenon and then increase the energy efficiency of the MaxMin algorithm. The proposed LQI-DCP protocol is compared to this optimized form of MaxMin in which there is no single-node cluster. Furthermore, many clustering potocols do not take efforts to sufficiently outspread clusterhead positions. In the state of the art, most of the papers give some performance criteria without showing how caryommes positioning are related to each other. To achieve better network efficiency, clusterhead locations should be choosen in a timely manner. This is the main goal of this work in which the link quality indicator (LQI) is used to improve caryommes positioning and then to enhance the energy efficiency.

III. The proposed LQI-DCP Clustering Protocol

The proposed distributed clustering protocol, called LQI-DCP, is based on the Link Quality Indicator (LQI). Intended to dense wireless sensor networks, its basic idea is to enhance the network efficiency by selecting the best located sensors as clusterheads. It takes place in 2 rounds. The first round consists of information exchanges to initialize the algorithm and to preselect preferable nodes. In this round, the undesirable nodes with respect to the preselected ones are identified. In the second round, caryommes are elected among the remaining non-clusterized nodes and the identified undesirable nodes in last resort.

The WSN can be modeled as a graph $G = (V, E)$, where two nodes are connected by an edge if they can communicate with each other. Let $x \in V$ be a node in the WSN. $\mathcal{N}_1(x)$ is the one-hop neighbourhood of the node x. A node x forms with each $y \in \mathcal{N}_1(x)$ a link of which the link quality indicator LQI value is denoted by $\ell(x, y) > 0$. For all other nodes $z \in V \setminus \mathcal{N}_1(x)$, $\ell(x, z) = 0$. Let ν be a bijective function defined in V which is a totally ordered set. The ν function is defined as follows:

$$\forall\, x \in\ V,\ \ \nu(x) = (f(x), id(x)) \tag{1}$$

where $f(x)$ is a criterion function (like the remaining energy, the degree of onnectivity) and $id(x)$ returns the address of the node x. The total ordering in V is defined as follows:

$\forall x \in V,\ \nu(x) > \nu(y) \iff (f(x) > f(y))\ or\ (f(x) = f(y)\ and\ id(x) > id(y))$

A. First Round

1) Firstly, all nodes are involved in a communication neighbourhood exchange in which, each node sends its criterion value to its respective neighbors.
2) A Node having the highest criterion value in its neighbourhood declare itself as a "Preselected Node" (PN). The set $\mathcal{S}_0$ of the preselected nodes is defined by:

$$\mathcal{S}_0 = \{x \in V,\ \forall\, y \in \mathcal{N}_1(x),\ \nu(x) > \nu(y)\} \tag{2}$$

3) A "Preselected Node" will announce its state by sending a "PN-INFORM-MSG" to its 1-hop neighbors.
4) A 1-hop neighbor of a "Preselected Node" which receives the "PN-INFORM-MSG" becomes a clusterized

node and belong to the cluster formed by the "preselected node". At this step, the set Ω_1 of the clusterized nodes is defined by :

$$\Omega_1 = \{x \in V,\, \exists\, y \in \mathcal{S}_0 \cap \mathcal{N}_1(x)\} \tag{3}$$

5) The "PN-INFORM-MSG" contains a parameter through which some nodes advertise themselves as the "Emissary Nodes" of the PN which has sent the "PN-INFORM-MSG". For each preselected node, its "emissary nodes" are some of the 1-hop neighbors which inform about the presence of the preselected node outside of the PN vicinity. Then the "emissary node" send to its 1-hop neighbourhood a "WBN-SELECTION-MSG" message containing a parameter which characterizes the "Whipping Boy Nodes" which are the nodes not desirable as clusterheads, if the "preselected node" were to be finally elected as caryomme. The "Whipping boy nodes" would have negative impacts on the network performance, if they were to be finally elected as clusterheads (because they are too near from the 1-hop neighbourhood of the PN). The idea is to choose the "Whipping boy nodes" in last resort. This helps outspreading the caryommes to optimize their relative positioning to each other (Fig. 1).
6) For this, each "Preselected Node" uses its weak links (small LQI value) to nominate its "emissary nodes", that is to say, the nodes which receive the "PN-INFORM-MSG" message and which forms with the PN a link having a quality under a given ℓ_{min} threshold. For a PN, each of its "emissary nodes" meanwhile uses its good links to designate its "whipping boy nodes" which are nodes which receive the "WBN-SELECTION-MSG" message and which form with the "emissary node" a link of which the quality exceeds a given ℓ_{max} threshold.
For each $x \in \mathcal{S}_0$, the set $\mathcal{K}_1$ of the emissary nodes is defined by:

$$\mathcal{K}_1(x) = \{y \in \mathcal{N}_1(x) \setminus \{x\}\, ,\, 0 < \ell(x,y) \leq \ell_{min}\} \tag{4}$$

Let $x \in \mathcal{S}_0$, for each $y \in \mathcal{K}_1(x)$, the set $\omega_1(x,y)$ of the whipping boy nodes is defined by:

$$\omega_1(x,y) = \{z \in V \setminus \mathcal{N}_1(x),\, \ell(y,z) \geq \ell_{max}\} \tag{5}$$

$$\varpi_1 = \cup_z \{z \in \omega_1(x,y),\, x \in \mathcal{S}_0,\, y \in \mathcal{K}_1(x)\} \tag{6}$$

7) A node which receives the "WBN-SELECTION-MSG" message from an "emissary node" with which it forms a link of which the quality is part of the link features of the "whipping boy nodes" takes the following decisions:
   - if the receiver node x_{wbn} is a PN which is not the sender of the "PN-INFORM-MSG" which has triggered the "WBN-SELECTION-MSG" message from "the emissary node", it becomes a "whipping boy node" and then loses its preselection. Therefore, its respective neighbors having no link with the PN become non-clusterized.

$$\mathcal{S}_0 = \mathcal{S}_0 \setminus \{x_{wbn}\} \tag{7}$$

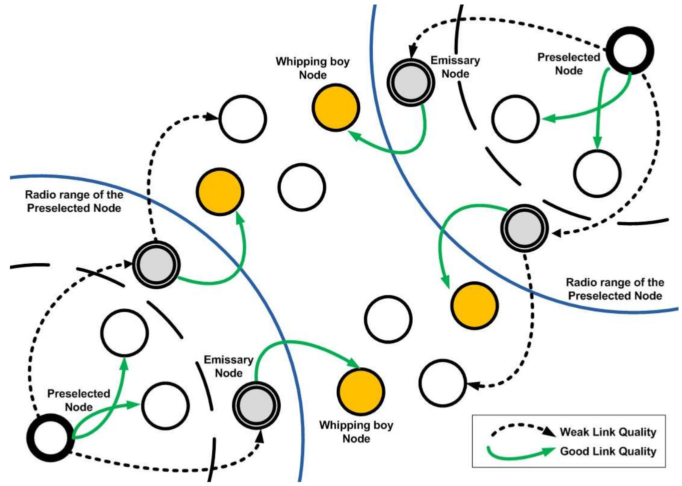

Fig. 1. Links and Node status in LQI-DCP

$$\varpi_1 = \varpi_1 \oplus \{x_{wbn}\} \tag{8}$$

   - If it is a non-clusterized node x_{ncn} which has no link with the PN (the sender of the "PN-INFORM-MSG" which triggered the "WBN-SELECTION-MSG"), then it becomes a "whipping boy node".

$$\varpi_1 = \varpi_1 \oplus \{x_{ncn}\}\, , \tag{9}$$

   - In all other cases, it ignores the "WBN-SELECTION-MSG" packet and if it is already a clusterized node, then it remains clusterized.

At the end of the first round, the set $\mathcal{S}_1$ of the first round elected clusterheads is defined by :

$$\mathcal{S}_1 = \mathcal{S}_0 \tag{10}$$

The set Ω_1 of the first round clusterized nodes is defined by :

$$\Omega_1 = \{x \in V,\, \exists\, y \in \mathcal{S}_1 \cap \mathcal{N}_1(x)\} \tag{11}$$

B. Second Round

This round involves the non-clusterized nodes and the whipping boy nodes identified during the first round (ϖ_1) plus the designated whipping boy nodes during the second round (ϖ_2). Initially,

$$\varpi_2 = \emptyset \tag{12}$$

$$\varpi_{2,0} = \varpi_1 \cup \varpi_2 \tag{13}$$

$$\mathcal{W}_{2,0} = \{E \setminus \Omega_1\} \setminus \varpi_{2,0} \tag{14}$$

1) During this round, each non-clusterized node x which is not a "whipping boy node" $(x \in \mathcal{W}_{2,0})$ triggers a timer $T_1(x)$ which is inversely proportional to its criterion value. Each "Whipping boy node" y $(y \in \varpi_1)$ triggers a timer $T_2(y)$ which is inversely proportional to its criterion value. If $\mathcal{W}_{2,0} \neq \emptyset$ and $\varpi_1 \neq \emptyset$ the timers T_1 and T_2 are set such that:

$$0 < T_{wait} < \max_{x \in \mathcal{W}_{2,0}} T_1(x) < \min_{y \in \varpi_{2,0}} T_2(y) \tag{15}$$

2) If no "CH-INFORM-MSG" message is sent after the waiting time T_{wait}, then there is no candidate (i.e $\mathcal{W}_{2,i} = \emptyset$ and $\varpi_{2,0} = \emptyset$). In this case, all clusterheads are known in the first round, then the clusterhead selection process stops at this step. Otherwise, At the expiration of the timer T_i $(i = 1, 2)$, the first node $w_{2,0}$ which has the highest criterion value informs its neighbourhood that it is a clusterhead, by sending a "CH-INFORM-MSG" packet. Let $w_{2,0}$ be the unique node in $E \setminus \Omega_1$ defined by:

$$if\ \mathcal{W}_{2,0} \neq \emptyset,\ \forall y \in \mathcal{W}_{2,0},\ \ \nu(w_{2,0}) > \nu(y) \tag{16}$$

$$if\ \mathcal{W}_{2,0} = \emptyset,\ \forall y \in \varpi_{2,0},\ \nu(w_{2,0}) > \nu(y) \tag{17}$$

3) The candidates, if any, send their "CH-INFORM-MSG" messages in the descending order of their respective criterion value. The sender $w_{2,i}$ of a "CH-INFORM-MSG" message becomes caryomme. Upon reception of a "CH-INFORM-MSG" message, each neighbor x_{ncn} which has not yet chosen a clusterhead, chooses the sender as caryomme and then cancels its timer.

$$if\ x_{ncn} \in \mathcal{W}_{2,0},\ \mathcal{W}_{2,0} = \mathcal{W}_{2,0} \setminus \{x_{ncn}\} \tag{18}$$

$$if\ x_{ncn} \in \varpi_{2,0},\ \varpi_{2,0} = \varpi_{2,0} \setminus \{x_{ncn}\} \tag{19}$$

4) As in the first round, upon reception of a "CH-INFORM-MSG" message, some neighbors which have not yet chosen a clusterhead, recognize themselves as "Emissary nodes" of the "CH-INFORM-MSG" sender. An "Emissary node", then informs its vicinity by sending its "WBN-SELECTION-MSG", which determines the "Whipping boy nodes" for the second round. Unlike the first round, a sensor having the characteristics of a "Whipping boy nodes" in the second round and which is already a clusterhead or a clusterized node keeps its status by ignoring the "WBN-SELECTION-MSG" message. Otherwise, it becomes a "Whipping boy node" (x_{wbn}) and then changes its timer value to T_3 so that it could be only elected in last resort (i.e $\max(T_2) < \min(T_3)$).

$$\varpi_2 = \varpi_2 \oplus \{x_{wbn}\} \tag{20}$$

Assuming that $\mathcal{W}_{2,i-1}$, $\varpi_{2,i-1}$ and $w_{2,i-1}$ are known in a previous step. Let $w_{2,i}$ be the unique node in $\mathcal{W}_{2,i-1} \cup \varpi_{2,i-1}$ defined by:

$$if\ \mathcal{W}_{2,i-1} \neq \emptyset,\ \forall y \in \mathcal{W}_{2,i-1},\ \nu(w_{2,i}) > \nu(y) \tag{21}$$

$$if\ \mathcal{W}_{2,i-1} = \emptyset,\ \forall y \in \varpi_{2,i-1},\ \nu(w_{2,i}) > \nu(y) \tag{22}$$

$$\mathcal{W}_{2,i} = \mathcal{W}_{2,i-1} \setminus \{\mathcal{W}_{2,i-1} \cap \mathcal{N}_1(w_{2,i-1})\} \tag{23}$$

$$\varpi_{2,i-1} = \varpi_{2,i-1} \setminus \{\varpi_{2,i-1} \cap \mathcal{N}_1(w_{2,i-1})\} \tag{24}$$

$$\varpi_{2,i} = \varpi_{2,i-1} \cup \varpi_2 \tag{25}$$

5) The second round stops at the expiration T_f of all timers.

$$T_f = \max(T_{wait}, \max(T_1), \max(T_2), \max(T_3)) \tag{26}$$

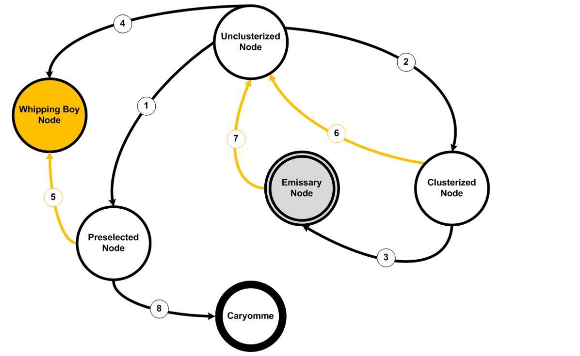

Fig. 2. LQI-DCP : Node State Transition in the 1st Round

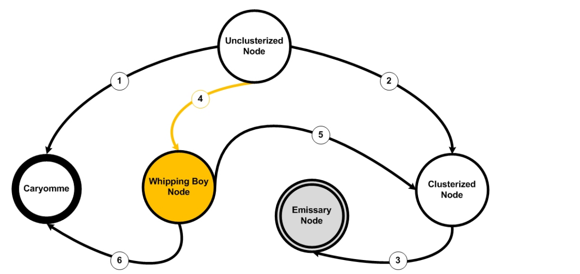

Fig. 3. LQI-DCP : Node State Transition in the 2nd Round

This occurs when $\mathcal{W}_{2,i} = \emptyset$ and $\varpi_{2,i} = \emptyset$. The set S_2 of the second round elected caryommes is defined by :

$$S_2 = \cup_i \{w_{2,i}\} \tag{27}$$

The set S of elected caryommes is defined by :

$$\mathcal{S} = \mathcal{S}_1 \cup S_2 \tag{28}$$

C. Using LQI-DCP for Multihop Clustering (d > 1)

In multihop d-clustering each node within a cluster is at most d hops away from its clusterhead. In the previous section, the presented LQI-DCP constructs one hop clusters in which each node can directly communicates with its clusterhead. After the selection of caryommes using the one-hop clustering form of LQI-DCP, d-clusters are then built, according to the known single-node cluster reduction (SNCR) mechanism we recall below. For more details, the SNCR mechanism is proposed in [7].

- Run LQI-DCP for $d = 1$ (first and second round).
- Once the set of clusterheads is known for $d = 1$, each caryomme initializes a timer T_S inversely proportional to its degree of connectivity.
- At the expiration of the timer T_S, the first caryomme which has the highest degree of connectivity, informs its neighbourhood that it is a selected clusterhead by sending a "CH-INFORM-MSG" packet.
- The "CH-INFORM-MSG" message contains the caryomme ID $id(CH_i)$ and has a time-to-live equal to d. It is retransmitted to all nodes within d-hops from the originating clusterhead.

- Upon reception of a "CH-INFORM-MSG" message, each neighbor which has not yet chosen a clusterhead, chooses the sender as caryomme, decrements the TTL and then forwards the "CH-INFORM-MSG" message to its neighbors.
- Upon reception of a "CH-INFORM-MSG" message, by another clusterhead, it creates a list "SRC-INFORM-LST" of senders which contains node IDs $id(S_i)$ of sensors from which the message is received. This node ID is not necessarily the one of the originating caryomme.
- The caryommes send their "CH-INFORM-MSG" messages in descending order of their respective degree of connectivity, until all caryommes have announced their state.
- A clusterhead of single-node cluster recognizes itself by the fact that its "CH-INFORM-MSG" message is not retransmitted by any of its neighbors. Such a clusterhead inspects its "SRC-INFORM-LST" list. If its list is not empty, it chooses the first node of its list as caryomme. If its "SRC-INFORM-LST" list is empty, then the clusterhead has no neighbor. This denotes a single-node cluster arising from the topology deployment of the WSN.

D. Maintenance Phase

Instead of entirely re-running the LQI-DCP protocol, it is sufficient to only run the SNCR mechanism to maintain the stability of cluster states when minor changes occur inside the wireless sensor network.

IV. Clusterhead Selection Criteria

To evaluate our LQI-DCP protocol, we use criteria functions presented is this section.

A. Sensor Proximity with respect to the Base Station (BS)

We consider a WSN deployed with a base station where each node knows its exact location and that of the BS. As the main goal of the application is to send events towards the BS, it seems natural to look at the criterion defined as follows:

$$C_i = 1/d(S_i, BS) \tag{29}$$

Where $d(S_i, BS)$ is the distance seperating the sensor S_i from the BS. We choose the inverse of the distance to promote the election of the closest sensor to the BS.

B. Degree of Connectivity

The degree of connectivity of a node, i.e. the number of its neighbors, is also a criterion that seems interesting to study. Intuitively, the more neighbors a sensor has, the more it seems to be an appropriate candidate as clusterhead, since a sensor with a low degree of connectivity might have little information, from its neighbourhood, to aggregate and to forward to the BS. In the initial phase, each sensor is involved in the neighbourhood information exchanges (hello protocol), which allows it to determine its degree of connectivity and the BS location.

C. Link Quality Indicator (LQI)

For moteiv′s Tmote Sky [20] sensors equipped with chipcon′s CC2420 [21], the LQI values range from 50 to 110. Even so, we stick with the ZigBee standard [1],[2]. Then, we use standard values (i.e. 0, 255), instead of those of CC2420. In this paper, we use the MinLQI clusterhead selection criterion defined in [7]. For a node, the MinLQI value represents the minimum LQI value beyond a given threshold between a node and its neighbours.

V. Cold Chain Monitoring Application

A. Network organization and deployment

The application is designed for a cold chain monitoring purpose. Its goal is to monitor a warehouse by logging alarms originating from sensors. Alarms are generated when the sensed temperature exceeds a given threshold. After a first phase consisting of hello exchanges, the LQI-DCP clustering algorithm is run. Then, each caryomme manages a TDMA organization (Fig. 4) by assigning one time slot ($T_{Slot}(S_i)$) to each one of its cluster members. To save energy, sensors switch in "sensing mode" and turn off their respective radios while leaving sensor modules in the active mode in order to continue collecting events. Then, in the data collection phase ($T_{Data} = 1s$) sensors wake up in turn upon their respective time slots in which each sensor sends its alarms to its respective caryomme. Since, the caryommes do not necessary form a connected backbone, all sensors wake up during the routing phase (Fig. 4) in which each caryomme aggregates the received alarms and then sends towards the BS. 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 [3]. It is run with the weighted round robin load balancing mechanism using the "MinLQI" metric. The routing phase ($T_{Routing} = 1min$) is followed by a long sleeping one ($T_{Sleep} = 8min59s$). With these time values, the total duration of a complete cycle (Sensing, Data collection, Routing) is $T_{Cycle} = 10min$. The assigned time slots to each regular clustered sensor are computed as follows:

$$T_{Slot}(S_i) = \frac{T_{Data}}{\eta_i} \tag{30}$$

Where η_i is the number of regular sensors which are in the same cluster as S_i.

In the simulation model N sensors are randomly deployed over an area of length $L = 200m$, and width $l = 200m$. The base station is located at the (0,0) location. Each node generates alarms, which are sensed data higher than the temperature threshold $Temp_{min}$, following the Poisson process of parameter $\lambda = 3$. The transmission range of each sensor (including the BS) is $R = 20m$.

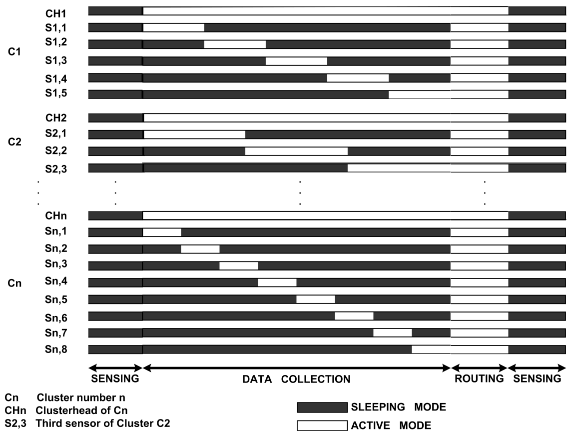

Fig. 4. Active/Sleep mode organization of the WSN

B. Energy Consumption Model

Let $E_{Tx}(k,d)$ the energy consumed to transmit a k bits message over a distance d [9]:

$$E_{Tx}(k,d) = E_{elec} * k + \varepsilon_{amp} * k * d^2 \tag{31}$$

Let E_{Rx} the energy consumed to receive a k bits message:

$$E_{Rx}(k,d) = E_{Rx-elec}(k) = E_{elec} * k \tag{32}$$

$$E_{elec} = 50nJ/bit \; and \; \varepsilon = 100pJ/bit/m^2 \tag{33}$$

The energy consumed by a sensor S_i in Active/Sleep modes is calculated following the model proposed by [22]:

$$E_{Radio}(S_i) = P_{Active} * T_{Active} + P_{Sleep} * T_{Sleep} \tag{34}$$

As in [22], $P_{Active} = 1040mW$ and $P_{Sleep} = 200mW$.

C. LQI Model for Simulation Purposes

The LQI values are calculated by using the $\ell(x,y)$ function defined below:

$$\ell(x,y) = \alpha + \frac{\beta * \log(1 + (\gamma(x,y) - \gamma_{min}(x)))}{\log(1 + \gamma_{max}(x))} \tag{35}$$

$$\gamma_(x,y) = \frac{1}{d(x,y)} \tag{36}$$

$$\gamma_{min}(x) = \min_{y \in \mathcal{N}_1(x)} \gamma(x,y) \tag{37}$$

$$\gamma_{max}(x) = \max_{y \in \mathcal{N}_1(x)} \gamma(x,y) \tag{38}$$

Where $\alpha = 50$, $\beta = 255$ and $d(x,y)$ is the distance separating y from x. The choice of this model is guided by experimental results shown in [23] and [24] which stated that the LQI decreases when the distance between nodes increases in Zigbee-based WSN. As we can see, $\ell(x,y) \neq \ell(y,x)$. Hence, the model allows to take into account asymetrical aspects of wireless links. This LQI model is only used for simulation purposes, so sensor nodes do not compute these above formulas.

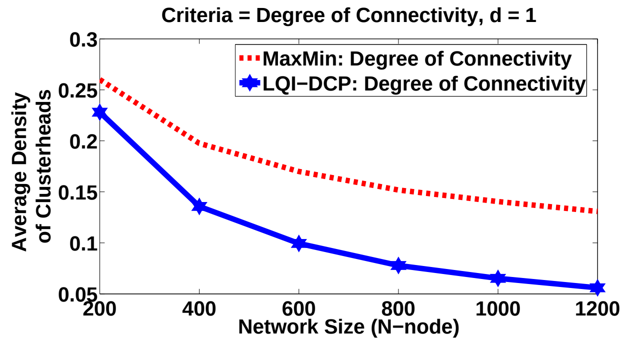

Fig. 5. Average density of clusterheads (Degree of Connectivity)

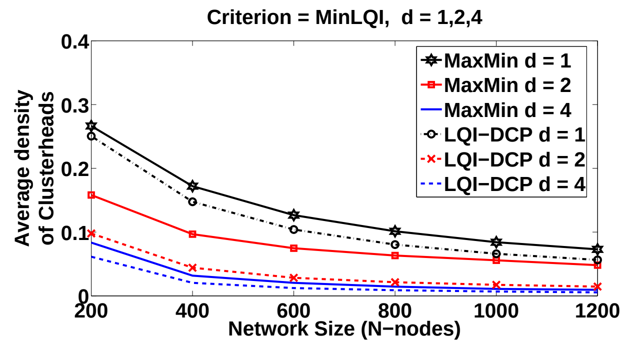

Fig. 6. Average density of clusterheads (MinLQI)

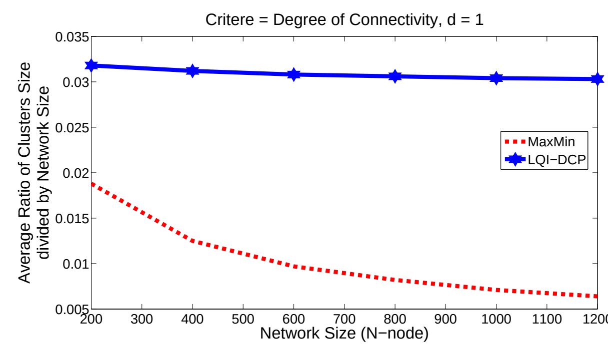

Fig. 7. Average Cluster Size divided by Network Size (Degree of Connectivity)

VI. Simulation Results

Simulations, using Matlab, are run for a network size ranging from 200 to 1200 nodes. The performance results presented here are obtained by averaging the results for 100 different simulations for each scenario, except for the scenario of the caryomme location (Fig. 11, 12 13, 14, 15 and 16) for which 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 $\ell_{min} = 70$. For the "MinLQI" criterion, the minimum LQI treshold is set to 100.

A. LQI-DCP Cluster Formation

The figures 5 and 6 show the average density of clusterheads both for LQI-DCP and MaxMin protocols, respectively for

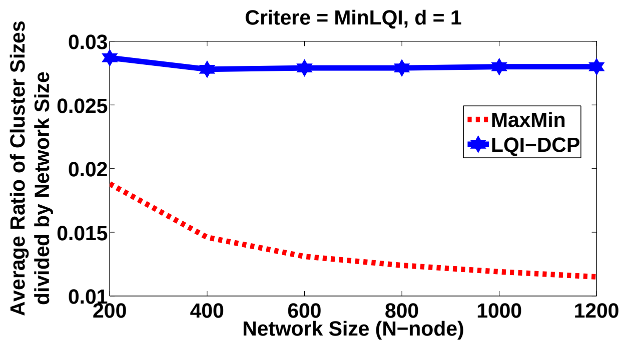

Fig. 8. Average Cluster Size divided by Network Size (MinLQI)

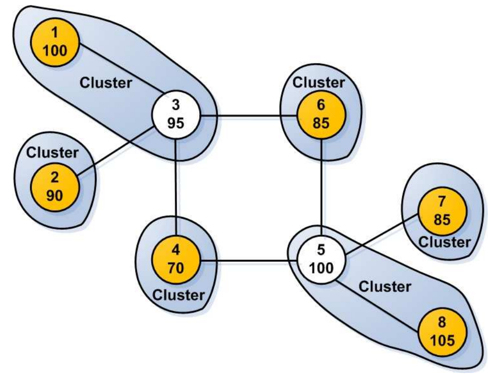

Fig. 9. LQI-DCP Clusters formed with indicated criterion values

the degree of connectivity and the MinLQI criteria. LQI-DCP leads to a caryomme density lower than MaxMin (whatever the value of d = 1,2,3,4). Differences may be more or less important depending on the criterion. Therefore, the cluster sizes (Fig. 7 and 8) are larger for LQI-DCP. When the number of caryommes is too important, energy efficiency decreases, so it is better to have a density of caryommes well suited to the density of the network deployment.

B. Single-Node Cluster Reduction (SNCR)

For LQI-DCP, the simulation results show a density of single-node clusters equal to zero for all studied criteria. Therefore, to avoid an additional energy consumption in the case of $d = 1$, it is not necessary to apply the single-node cluster reduction (SNCR) mechanism immediately after the second round. This does not mean that LQI-DCP produces no single-node cluster. Indeed it could meet some cases arising from the deployment topology of the WSN, where the density of single-node clusters can be less or larger. For example, consider the network (Fig. 9), for which it is assumed that there is no whipping boy nodes (nor in the first round, nor in the second one). That is to say that the nodes are sufficiently outspread so that any link quality between two nodes does not meet the conditions of the equation (4). For this network, LQI-DCP (ran for d = 1) produces nodes 1, 2, 4, 6, 7 and 8 as caryommes. In such a case, clusters represented by nodes 2, 4, 6 and 7 are single-node clusters (Fig. 9). However, if we choose the degree of connectivity criterion to form cluster in this example, we get after the first round the two clusters represented by nodes 3 and 5 (Fig. 10). Anyway, the results for these types of cases tightly rely on the function criterion used to form clusters. Moreover the deployment topologies such that there is neither whipping boy node nor enough node density are types of WSN deployments that lead to negative impacts on the network performance whatever the protocol considered. For such cases it would be better to revise the initial network deployment conditions. On the happening of a single-node cluster phenomenon after the secound round of the LQI-DCP clustering scheme, the fact of using the SNCR mechanism in the maintenance phase could help mitigating this phenomenon.

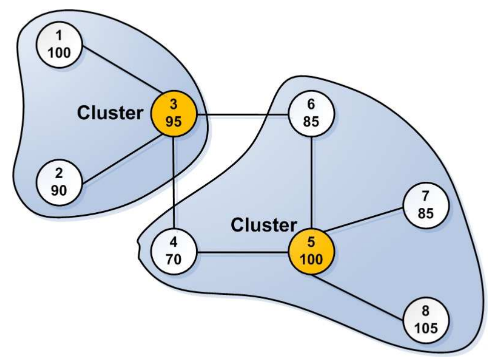

Fig. 10. LQI-DCP Clusters formed with the degree of connectivity criterion

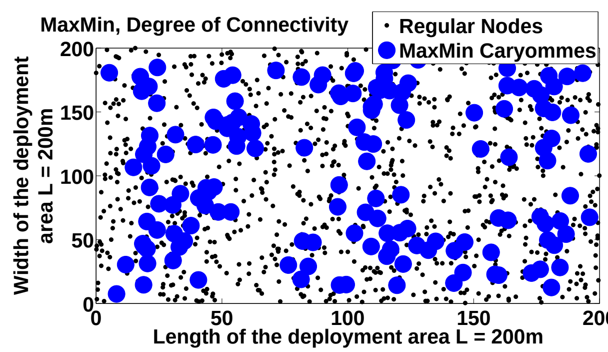

Fig. 11. Positions of caryommes (MaxMin, Degree of Connectivity, d=1)

C. Positions of Caryommes

The Figures 11, 13 and 15 display the position of clusterheads selected by MaxMin combined with the single-node cluster reduction (SNCR) mechanism. The Figures 12, 14 and 16 display the position of clusterheads selected with LQI-DCP used in its one-hop clustering form (1st and 2nd rounds). For the MinLQI criterion (Fig. 15, 16), as in [7], we use a 100mx100m deployment area of 500-nodes WSN.

The results show that our objective of sufficiently outspreading the caryommes, to optimize their relative positions to each other, is achieved. Indeed, for all the studied criteria, LQI-DCP produces clusterheads which are sufficiently outspread. This denotes better locations for clusterheads. This is due to

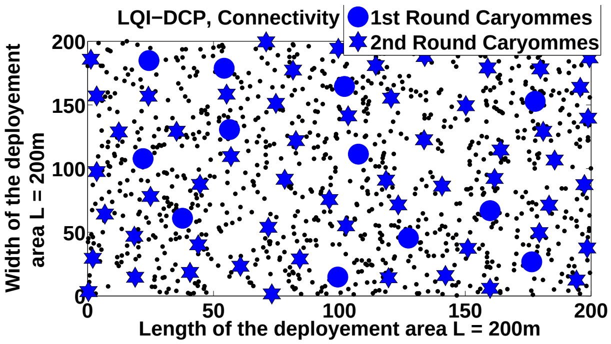

Fig. 12. Positions of caryommes (LQI-DCP, Degree of Connectivity, d=1)

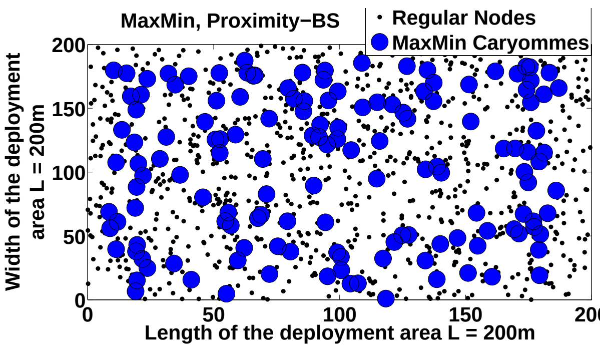

Fig. 13. Positions of caryommes (MaxMin, Proximity-BS, d=1)

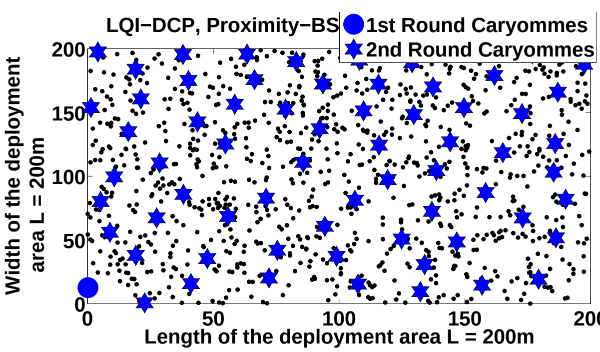

Fig. 14. Positions of caryommes (LQI-DCP, Proximity-BS, d=1)

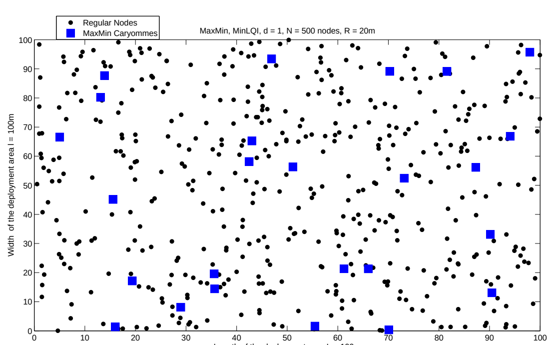

Fig. 15. Positions of caryommes (MaxMin, MinLQI, d=1)

the fact that the whipping boy nodes are only elected in last

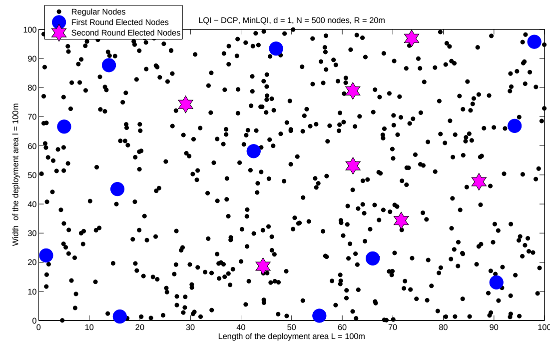

Fig. 16. Positions of caryommes (LQI-DCP, MinLQI, d=1)

resort. As for MaxMin, these results show that the locations of caryommes are less optimal when the "Proximity with respect to the BS" (Fig. 13) and the "degree of connectivity" (Fig. 11) are used as criterion. As for MinLQI (Fig. 15), clusterheads are sufficiently outspread which denotes better locations for clusterheads, but less than those of the LQI-DCP protocol (Fig. 16). The locations of caryommes generated by the degree of connectivity criterion in MaxMin are not optimal because if a node has a high degree of connectivity, then its closest neighbors also have a high degree of connectivity. So this criterion promotes the creation of neighboring nodes as clusterheads. Likely, for the "Proximity with respect to the BS" criterion in MaxMin, if a node is close to the BS, its nearest neighbors are also close to the BS. Conversely, choosing the MinLQI criterion promotes the election of sensors enough apart from each other. This leads to a better geographical distribution of caryommes. If the caryommes are not sufficiently separated from each other, this affects the energy efficiency of the network. Indeed, when a "regular node" communicates with its own caryomme, the other neighboring caryommes hear the communication which is not intended to them. Therefore the energy consumption increases. Furthermore the risk of collision also increases because two neighboring nodes which have distinct clusterheads could try to communicate simultaneously with their respective clusterheads which are also in the same radio range. For LQI-DCP, the results distinguish caryommes elected in the first round of those elected in the second one. The specificity of the "Proximity with respect to the BS" criteria is that it gives only one elected caryomme in the first round (Fig. 14). This result is expected, because as the set E is totally ordered, each node in its neighbourhood has at least one other node which is closest to the base station, except for the single node of the network which is the closest sensor to the base station. Precisely, this is the only elected sensor in the first round (Fig. 14).

D. Grid Deployment Topology

The grid deployment topology is often used in the context of the WSN deployed in a warehouse which hosts a large number of pallets, one upon the other, organized in several line-up separated to each other by lanes. So simulation results

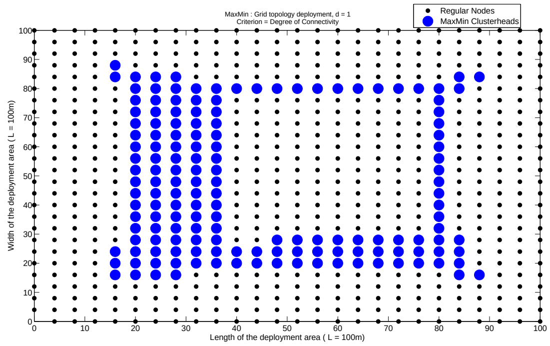

Fig. 17. Positions of caryommes (MaxMin, Degree of Connectivity, d=1)

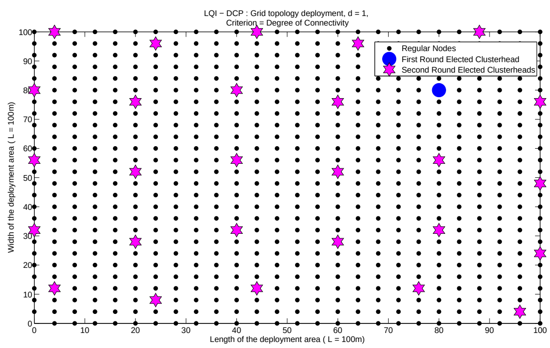

Fig. 18. Positions of caryommes (LQI-DCP, Degree of Connectivity, d=1)

presented in this section are pertaining to the grid topology deployment of the WSN. The figure 17 displays the caryomme locations produced by MaxMin for the degree of connectivity criterion. This is the known pathological configuration where MaxMin fails to provide good solution [4] because in each straight line, the degree of connectivity is monotically increasing. We recall this pathological case to show that our LQI-DCP protocol can mitigate this issue (Fig. 18) without changing the foremost chosen conditions of the network deployment. In a warehouse, due to the physical environment, the WSN deployed to monitor the cold chain might encounter the grid topology requirement. With the MaxMin heuristic, it is possible to use a randomly distributed criterion (Fig. 19) in order to mitigate this phenomenon. In that case LQI-DCP, also provide more interesting results (Fig. 20)

E. Energy Consumption

The application consists of three main phases: the clustering formation phase, the data collection phase and the routing phase (Fig. 4). 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 figures 21 and 22 display the clustering phase energy consumption for both protocols when the degree of connectivity and the "proximity with respect to the BS" criteria are used. In the clustering phase, LQI-DCP

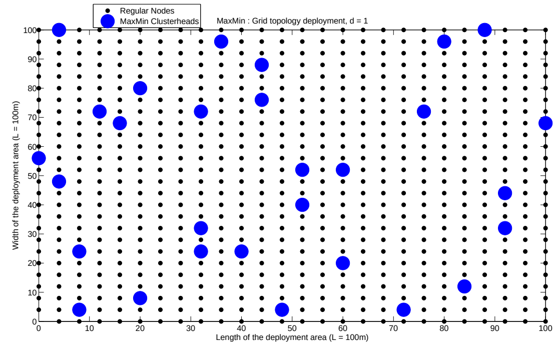

Fig. 19. Positions of caryommes (MaxMin, Remaining Energy Criterion, d=1)

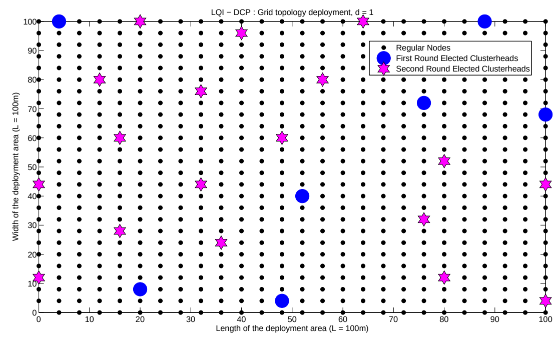

Fig. 20. Positions of caryommes (LQI-DCP, Remaining Energy Criterion, d=1)

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 a lower energy consumption. It is the same for the phases of data collection (Fig. 23,24) and routing (Fig. 25,26). For both phases the gap is important because the locations of the caryommes from MaxMin are worse compared to LQI-DCP. Consequently, in the data collection phase, when a sensor sends its data to its respective caryomme, other proximate caryommes hear the communication which is not intended to them. This has the effect of increasing the energy consumption. In the routing phase, only caryommes send their aggregated data to the base station. As the number of caryommes is higher for MaxMin than LQI-DCP, the energy consumed is much more higher for MaxMin compared to LQI-DCP. Therefore the overall energy consumption for a complete cycle (Clustering + Data Collection + Routing) is much more higher for MaxMin compared to LQI-DCP which is more energy efficient (Fig. 27,28).

The figures 29 and 30 show for each protocol the ratio

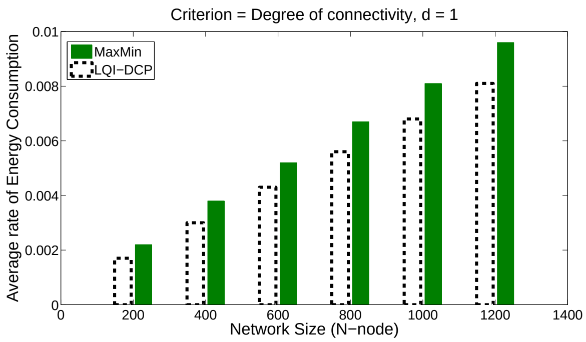

Fig. 21. Average rate of energy consumption (Clustering Phase, d=1)

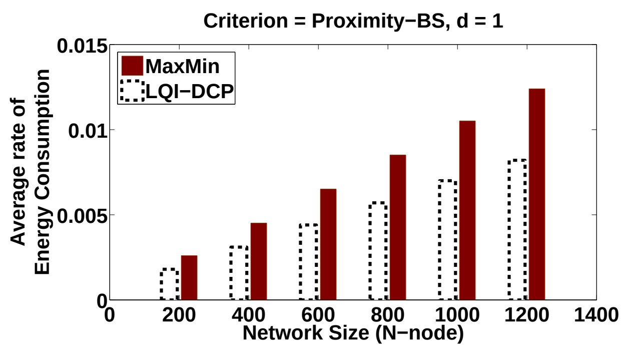

Fig. 22. Average rate of energy consumption (Clustering Phase, d=1)

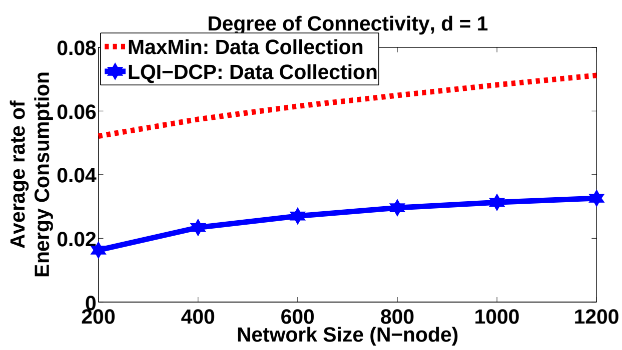

Fig. 23. Average rate of energy consumption (Data Collection Phase, d=1)

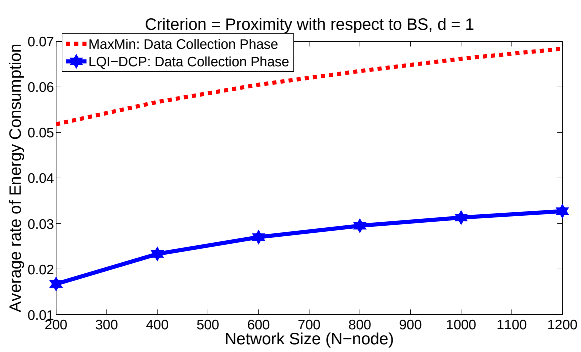

Fig. 24. Average rate of energy consumption (Data Collection Phase, d=1)

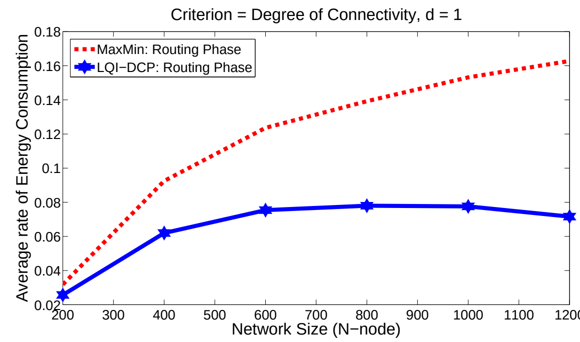

Fig. 25. Average rate of energy consumption (Routing Phase, d=1)

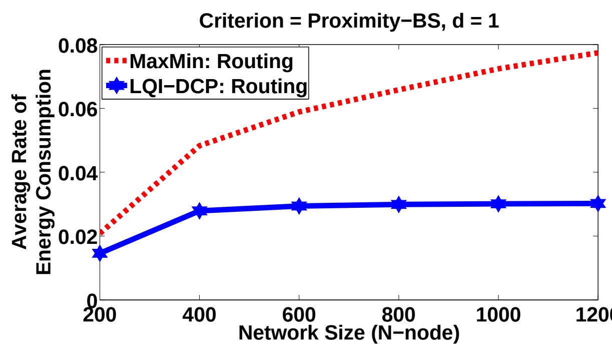

Fig. 26. Average rate of energy consumption (Routing Phase, d=1)

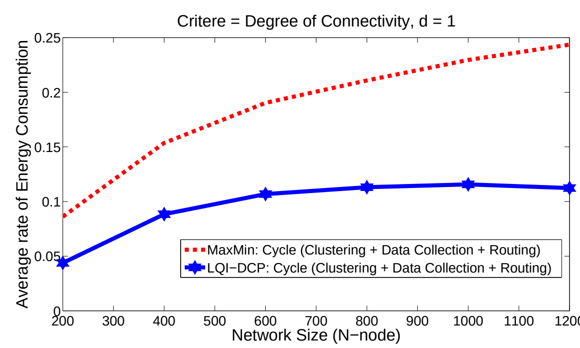

Fig. 27. Average rate of energy consumption for one cycle (d=1)

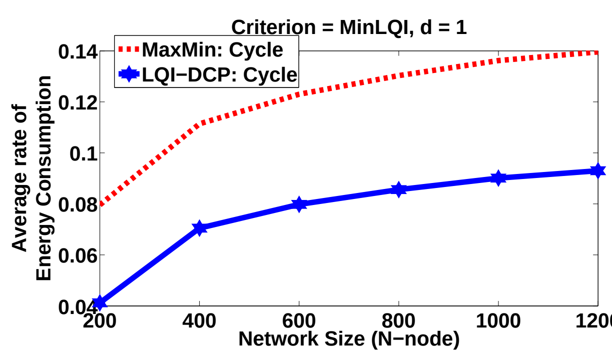

Fig. 28. Average rate of energy consumption for one cycle (d=1)

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

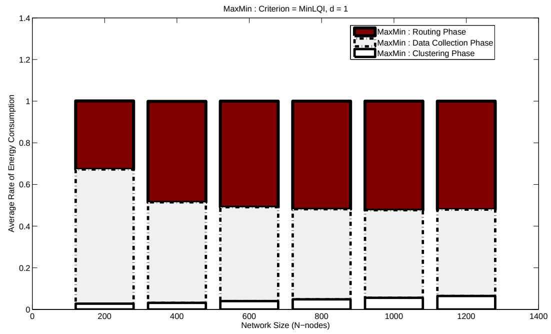

Fig. 29. Average ratio of energy consumption per phase (MaxMin, d=1)

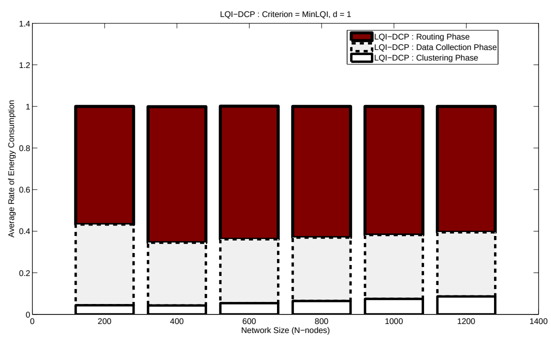

Fig. 30. Average ratio of energy consumption per phase (LQI-DCP, d=1)

energy expenditure during one cycle for the same MaxMin protocol. This result depends on the selection criterion. The previous results (Fig. 21, 22, 23, 24, 25, 26, 27 and 28) show 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 is more important in LQI-DCP (60%) than in MaxMin (55%). 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.

F. Impacts of the Unreliability of the Wireless Links

In the context of our 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:

$$Pr\left[\ell ink(i,j) = unreliable\right] = 1\ ,\ if\ \delta(i,j) \leq p \qquad (39)$$

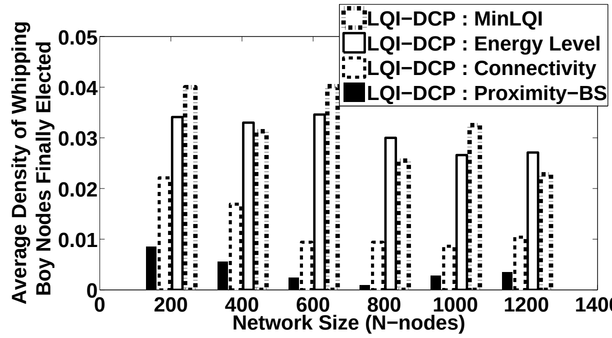

Fig. 31. Average Density of Whipping Boy Nodes Finally Elected as Clusterheads (LQI-DCP, d=1)

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 $Pr\left[\ell ink(i,j) = unreliable\right] = 1$, then the node S_j would not be a whipping boy node related to the emissary node S_i even if $\ell(i,j) \geq \ell_{max}$.

Before inspecting the impacts of the unrelibility 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. Then the figure 31 plots the average number of whipping boy nodes finally elected 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 and between 3% and 4% for the MinLQI criterion. The Fig. 32 shows the effect of the unreliability of the wireless links 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 clusterhead selection criterion. The Fig. 33 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. These results show that the unreliability of the wireless links has negligible effects on the LQI-DCP behaviour. 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.

VII. Conclusion

In this paper, we have presented a new protocol (LQI-DCP) of cluster formation based on the link quality indicator (LQI). It is a distributed protocol which aims to construct d-hops clusters, that is to say d-dominant sub-sets of wireless sensor networks where each node within a cluster is at most at d wireless hops away from its clusterhead. The LQI is defined

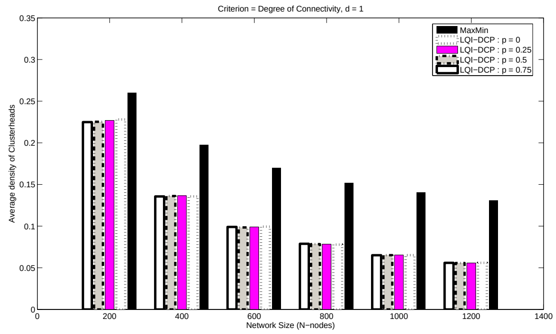

Fig. 32. Average Density of Clusterheads (LQI-DCP, Degree of Connectivity, d=1)

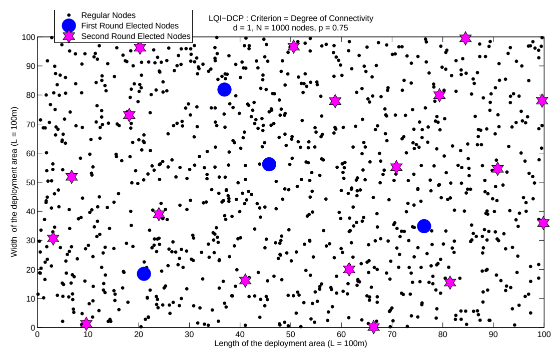

Fig. 33. Average Positions of Clusterheads (LQI-DCP, Degree of Connectivity, d=1, p = 0.75)

in the 802.15.4 standard, but its context of use is not yet specified in the standard. We have therefore proposed the use of the link quality for the cluster formation in WSN. The idea is based on the fact that the LQI gives an idea of the distance separating the two nodes that form the link. Indeed, the LQI decreases as the distance increases. To avoid using the expensive GPS technology which cannot also be used everywhere, it is useful to exploit the LQI that is already defined at the MAC layer of Zigbee based WSNs. The second objective was to propose a cluster formation where clusterheads are sufficiently outspread from each other to increase the overall performance of the network. Therefore, LQI-DCP is an algorithm which runs in two rounds, where the first preselected nodes trigger the elimination of some sensors called the "whipping boy nodes". In accordance with the preselected node locations, the "whipping boy nodes" would have negative impacts on the network performance, if they were to be finally elected as clusterheads. We compared LQI-DCP to the generalized form of the MaxMin protocol run with the single-cluster nodes reduction mechanism. Simulations show that the rate of "whipping boy nodes" finally elected is quite low, our proposed LQI-DCP decreases the density of elected caryommes, gives better positions of caryommes, and then increases the energy efficiency of the network.

References

[1] IEEE Std 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.

[2] Zigbee Alliance. Zigbee specification v1. Jun. 2005.

[3] C. Diallo, M. Marot, and M. Becker. Link quality and local load balancing routing mechanisms in wireless sensor networks. In *Proc. of the 6th Advanced International Conference on Telecommunications, AICT 2010*, Barcelona, Spain, May 2010 (to be published).

[4] A.D. Amis, R. Prakash, T.H.P Vuong, and D.T. 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] A. Delye de Clauzade de Mazieux. Etude théorique des clusters multi-sauts dans les réseaux de capteurs sans fils. In *Thèse de doctorat*, Université Paris VI, 2007.

[6] A. Delye 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.

[7] C. Diallo, M. Marot, and M. Becker. Single-node cluster reduction in wsn and energy-efficiency during cluster formation. In *Rapport de Recherche no 10004-RST*, TELECOM SudParis, Jan. 2010.

[8] C. Gao and R. Jantti. Link-state clustering based on ieee 802.15.4 mac for wireless ad-hoc/sensor networks. In *Proc. IEEE Wireless Communications and Networking Conference, WCNC 2006, Volume 1, Page(s):499 - 504*, Las Vegas, NV USA, Apr. 2006.

[9] W. B. Heinzelman, A. Chandrakasan, and H. Balakrishnan. An application-specific protocol architecture for wireless microsensor networks. *IEEE Transactions on Wireless Communications, Vol. 1(4)*, pages 660–670, Oct. 2002.

[10] S. Fazackerley, A. Paeth, and R. Lawrence. Cluster head selection using rf signal strength. In *Proc. of Canadian conference on electrical and computer engineering, CCECE*, Newfoundland, Canada, May 2009.

[11] F. Dai and J. Wu. On constructing k-connected k-dominating set in wireless networks. In *Proc. of the 19th IEEE international Parallel and Distributed Processing Symposium, IPDPS'05, Vol. 01*, Washington, DC, USA, Apr. 2005.

[12] M.R. Brust, H. Frey, and S. Rothkugel. Dynamic multi-hop clustering for mobile hybrid wireless networks. In *ACM Proc. of the 2nd international Conference on Ubiquitous information Management and Communication, ICUIMC'08, Vol. 01*, Suwon, Korea, Jan. 2008.

[13] Y. Liu, J. Gao, L. Zhu, and Y. Zhang. A clustering algorithm based on communication facility in wsn. In *WRI International Conference on Communications and Mobile Computing, CMC '09, Vol. 2*, pages 76–80, Jan. 2009.

[14] F. G. Nocetti, J. S. Gonzalez, and I. Stojmenovic. Connectivity based k-hop clustering in wireless networks. *Telecommunication Systems, Vol. 22, Numbers 1-4*, pages 205–220, Jan. 2003.

[15] O. Younis and S. Fahmy. Distributed clustering in ad-hoc sensor networks : a hybrid, energy-efficient approach. In *Proc. of IEEE Infocom 2004*, Hong Kong, Mar. 2004.

[16] M. Qin and R. Zimmermann. An energy-efficient voting-based clustering algorithm for sensor networks. In *Proc. of the 6th International Conference on Software Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing and First ACIS International Workshop on Self-Assembling Wireless Networks (SNPD/SAWN)*, 2005.

[17] J.Y. Cheng, S.Ruan, R.Cheng, and T.Hsu. Padcp: Power-aware dynamic clustering protocol for wireless sensor network. In *IFIP International Conference on Wireless and Optical Communications Networks (WOCN)*, Apr. 2006.

[18] K. Sun, P. Peng, P. Ning, and C. Wang. Secure distributed cluster formation in wireless sensor networks. In *Proc. of the 22nd Annual Computer Security Applications Conference*, pages 131–140, Dec. 2006.

[19] K. Iwanicki and M. v. Steen. Multi-hop cluster hierarchy maintenance in wireless sensor networks: A case for gossip-based protocols. In *6th European Conference on Wireless Sensor Networks, EWSN 2009*, Cork, Ireland, 2009.

[20] Tmote Sky. http://www.snm.ethz.ch/projects/tmotesky. Last access, Mar. 2010.

[21] CC2420 Radio. http://www.chipcon.com. Last access, Mar. 2010.

[22] E. Shih, S.-H. Cho, N. Ickes, R. Min, A. Sinha, A. Wang, and A. Chandrakasan. Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks. In *ACM MobiCom*, Rome, Jul. 2001.

[23] 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*, 2007.

[24] 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 2009, LNCS 5550*, pages 14–25, NETWORKING, Aachen, Germany, 2009.