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# Efficiency Benefits Through Load-Balancing with Link Reliability Based Routing in WSNs

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***Abstract*—In wireless sensor networks (WSN) energy efficiency of routing protocols is of primary importance. Embedded with local load balancing mechanisms, the proposed L2RP protocol is a link reliability based routing protocol which aims to help source nodes to exploit the potential capabilities of their respective neighbors. As it is a reliability-oriented protocol, L2RP discards unreliable links to avoid the substantial energy cost of packet losses. Simulation results show major efficiency benefits that stem from load balancing which helps in lengthening the network lifetime while minimizing packet losses.**

**In WSN, the choice of a routing protocol and its key parameters depends on the nature of the application and on its primary mission. Lot of works addressed routing issues with more or less effectiveness, some of which pointed out the use of the link quality indicator (LQI) as a route selection criterion (metric). In a previous work, following an experimental study, we have shown, under some conditions, the inefficiency of the LQI based routing. In this paper, we propose through L2RP a simple way to improve reliability and efficiency of the LQI based routing in WSN. We also give a comparative study of several metrics including new definitions of LQI based metrics. Simulation results show that our adaptation of the LQI metric is among the best route selection criteria regardless of the performance criterion under consideration.**

***Index Terms*—Wireless Sensors Networks (WSN); Load-Balancing Routing; LQI; L2RP; Energy Efficiency.**

## I. INTRODUCTION

Designing a cold chain monitoring application requires special focus on at least two main phases. In [2], we presented an example of sensor network for cold chain monitoring where sensors are inside pallets. We proposed energy efficient protocols for the transport phase in which the WSN is deployed in trucks with no Base Station (BS) because it would be very expensive to install and maintain Base Stations within each truck. There are a few sensors in the truck.

The second phase concerns the product storage in a warehouse where each pallet is handling temperature sensor. 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. Due to the size of a warehouse which hosts large number of pallets, one upon the other, the WSN can reach several hundreds of sensors which collaborate for sending data towards the BS. So, in this environment, the link quality is a key parameter which has many effects on the network performance.

In [3], we used up to 50 Moteiv Tmote Sky [4] sensors, in a small experimental platform, including a 2.4GHz ZigBee [5][6] wireless transceiver (chipcon′s CC2420) [7]. On each packet reception, the CC2420 calculates the error rate, and produces a LQI value. To conduct experiments, we used the multiHopLQI[1] routing algorithm along with the Sensornet Protocol (SP) implementation [8]. In this algorithm, nodes sense and send "interesting events" to the BS. Based on the acknowledgement, a sensor decides to retransmit the data or not. If the acknowledgement fails, the sensor selects another node and routes data towards the BS. Under these conditions, the experimental results pointed out that the LQI based routing could have negative effects on the network performance [3].

After all, we think that the link quality might be a key parameter which some routing protocols could rely on in order to increase the network performance. The link quality indicator (LQI) is defined in the IEEE 802.15.4 standard [5][6] as a measurement of the quality of packet reception between two nodes. The IEEE 802.15.4 standard does not specify the implementation of LQI, which is up to the radio manufacturer. Several works address WSN routing, but only few papers are related to LQI based routing protocols. Sensors are characterized by their low energy level. Thereby load balancing traffic between different nodes, is also an essential idea to increase the lifetime of nodes and thus the network. This work addresses two challenges: improving LQI based routing protocol by load balancing traffic over multiple paths.

When a sensor has to send data towards the Base Station, the load balancing routing consists to elect several nodes as next hop routers depending on the order of packet transmissions and the nodes previously used as the next hop routers. The idea is to involve several sensors in the routing effort to minimize the overall energy consumption and then extend the network lifetime.

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[1] http://www.tinyos.net/tinyos-1.x/tos/lib/MultiHopLQI

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The metric is a property of a route in computer networking consisting of any value used by routing algorithms to determine whether one route should perform better than another. Commonly, the route with the lowest metric is the preferred route. However, in this paper, a metric means the local value associated with a node: for a source node, the highest value, in its neighbourhood, may lead to the selection of such a node as the next hop router. For instance, The remaining energy level can be used as a metric to promote the selection of the highest powered nodes as next hop routers.

In this paper, we propose WSN local load balancing routing mechanisms using the Wait and See (WaS) protocol [2] by comparing the following metrics: the remaining energy level, the degree of connectivity (number of neighbors), the sensor proximity with respect to the Base Station, the link quality indicator (LQI), and a hybrid metric composed of any pairs of these metrics.

The sensor networks are characterized by low energy constituting their batteries. Then energy consumption and some other performance criteria such as the load imbalance factor (LIF), the average path lengths, the network lifetime and the packet loss percentage are taken into consideration to evaluate the effectiveness of routing mechanisms.

***"Achtophorous Node" definition***: we focus on homogeneous WSN where all sensors are participating together in the routing effort. Since all nodes are routers, we prefer using the term "achtophorous node" derived from Greek term $\alpha\chi\theta o\varphi o\rho\varepsilon\omega$ which denotes "node handling heavy load". For each node sending data, its achtophorous nodes are its next hop sensors which handle the load due to the routing of its packets towards the BS. Each sensor selects among its neighbors one or more achtophorous nodes. We also examine the influence of increasing the number of the achtophorous nodes on the routing efficiency. The WSN deployed in a warehouse is proned to some unreliabilities of wireless links. Then, we present results pertaining to unreliable links impacts on the network performance.

The rest of this paper is organized as follows. After presentation of a short background in the next part, the next one gives some topics on studied metrics (Section III). Then, we describe load balancing mechanisms (Section IV) and the proposed routing protocol (Section V). Finally, the last two sections present the simulation model and the results.

## II. RELATED WORKS

Commonly used by the TinyOS community, MultihopLQI is a routing protocol which employs the cost-based paradigm defined in [9]. Link estimation is viewed as an essential tool for the computation of reliability-oriented route selection metrics. In MultiHopLQI, the link metric is the Link Quality Indicator (LQI) which is used additively to obtain the cost of a given route. MultihopLQI avoids routing tables by only keeping state for the best parent at a given time, drastically reducing memory usage and control overhead. A new parent is adopted if it advertises a lower cost than the current parent.

Many experimental studies related to WSN, some of which are based on MultiHopLQI, [3][10][11][12][13][14][15][16] have shown that high unreliability of wireless links must be explicitly taken into account when designing routing protocols. [11][12] address load balancing embedded in reliability-oriented routing protocols and are also using MultiHopLQI.

In [17][18] authors address the problem of minimizing the total consumed energy to reach the destination. The performance objective of maximizing the network lifetime was considered in [19][20].

Several works are related to WSN and ad hoc networks load balancing routing schemes [21][22][23][24][25][26]. In [21], authors show that distributing the traffic generated by each sensor node through multiple paths instead of using a single path allows energy savings. Paper [22] defines a network optimization problem used for performing the load balancing in wireless networks with a single type of traffic. In [23], authors study wireless network routing algorithms that use only short paths, for minimizing the latency, and achieve the load balance. In [24], authors introduce a collision awareness in multipath routing; while [25] propose a multipath routing protocol to address the congestion control issue in WSN. In [26], the challenge of maximizing the network lifetime by load balancing the traffic is covered. In order to balance the energy consumption among sensor nodes, they deploy multiple sinks simultaneously, which are connected through wired or wireless infrastructure. [27][28] and [29] are also related to load balancing routing protocols.

The paper [30] presents a resource-aware and link quality based (RLQ) routing metric. Based on both energy efficiency and link quality statistics, the RLQ metric in [30] is intended to adapt to varying wireless channel conditions, while exploiting the heterogeneous capabilities. This protocol does not include load balancing features.

Some works are taken into account the round-robin cluster based routing [31][32] and [33], where clusterheads are selected on a round-robin fashion. In [34] authors propose a source count (packets) based weighted round-robin forwarding algorithm.

Although all these studies provide a valuable and strong contribution in WSN routing, the problems of load balancing routing mechanisms based on local metrics, with special interest on the LQI based metrics, are yet to be addressed. This is the goal of this paper. To save energy, we exploit the broadcast nature of wireless links, and the fact that the weights, in our proposed L2RP protocol, are built upon the achtophorous nodes capabilities instead of the ones of the source node. This allows L2RP to avoid doing a per packet load-balancing by the source, as done in [34], where the source node sends its data without being sure that the achtophorous node is able or not to sustain the load assigned. Thus, L2RP hleps in reducing packet losses. Moreover, in most of papers addressing the load balancing routing, both experimental studies and simulation models are validated for only small sized networks (few tens of nodes), whereas our work addresses large sized networks (several hundreds of sensors). The comparative study of different metrics in L2RP is also a contribution of this paper.

## III. ROUTES SELECTION CRITERIA

In this paper, "metric" is used to refer to local route selection criterion. As defined in introduction, each time we use "Achtophorous Node" it means next hop router with respect to a specific node having data to transmit towards the BS.

### A. Remaining Energy Level

The remaining energy of sensors could be a metric for selecting routes since a node with better battery life seems to be a better candidate for the packet routing from its neighbors. Conversely, if a sensor with low power is selected as an achtophorous node, this can lead to packet losses because it might not have enough batteries to forward packets. In this paper, we consider that each node knows its energy level.

### B. Sensor Proximity with respect to the Base Station (Proximity-BS)

Fig. 1. Pallets arrangement inside a warehouse

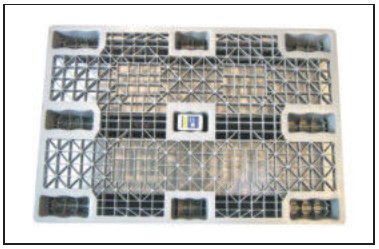

Fig. 2. Sensor plugged inside a Pallet

Fig. 3. Location of a pallet: lane, location and level

In a warehouse (see Figure 1), depending on the nature of their respective contents (frozen foods, fresh produce, etc.), the pallets provided each with a sensor (see Figure 2) are arranged in fixed locations (see Figure 3) designated by the Warehouse Management Software (WMS). Thus, during the warehouse WSN initialization, sensors could be initialized with their respective positions without using the GPS technology.

So, we consider a WSN deployed with a Base Station where each node knows its exact position and that of the BS. As the main goal of the application is to send data towards the BS, it seems natural to look at the metric defined as follows:

$$ProximityBS(S_i, BS) = 1/d(S_i, BS) \quad (1)$$

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

### C. Degree of Connectivity

The degree of connectivity of a node, i.e., the number of its neighbors, is also a metric that seems interesting to study because, intuitively, the more neighbors a sensor has, the more it seems to be an appropriate candidate as an achtophorous node since a sensor with a low degree of connectivity might have little information, from its neighbourhood, 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 position.

### D. LQI: Link Quality Indicator

In Zigbee standard [5][6], 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 [5][6]. 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 [5][6].

For moteiv′s Tmote Sky [4] sensors equipped with chipcon′s CC2420 [7], the LQI values range from 50 to 110. Even so, we stick with the ZigBee standard [5][6] because some manufacturers, such as SUN-SPOT [35] and WiEye [36], are still using the standard LQI values. Then, we use

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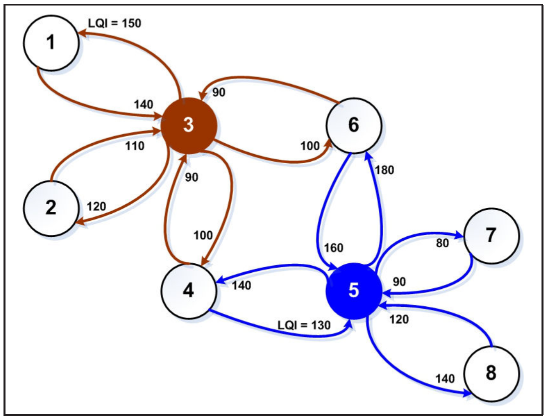

Fig. 4. Example of a WSN with Asymetrical Links

TABLE I
LQI METRIC VALUES RELATED TO THE WSN IN FIGURE 4

| ***Sensor ID*** | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** | ***6*** | ***7*** | ***8*** |
|---|---|---|---|---|---|---|---|---|
| ***AvgLQI*** | 150 | 120 | 107.5 | 120 | 125 | 140 | 80 | 140 |
| ***MaxLQI*** | 150 | 120 | 140 | 140 | 160 | 180 | 80 | 140 |
| ***MinLQI*** | 150 | 120 | 110 | 100 | 120 | 100 | 80 | 140 |

the standard values (i.e., $[0, 255]$), instead of those of CC2420.

In this paper, we define three LQI based metrics: AvgLQI, MaxLQI and MinLQI. The AvgLQI metric is the average calculated from the LQI values of all the links between the node and its neighbors. AvgLQI values give a characterization of sensors throughout their respective coverage quality. This metric might be useful in the context of the WSN deployed in a warehouse which hosts a large number of pallets, one upon the other. Such an environment is proned to high unreliability of wireless links. the MaxLQI metric is the maximum LQI value which matches to the standard definition of the LQI used in the MultiHopLQI routing algorithm [3][8]. As for the MinLQI, it is the minimum value beyond the given LQI threshold. For example (see Figure 4), assuming that the LQI threshold for an acceptable link quality is 100, the MinLQI for node 5 is 120 (LQI of link 5-8) instead of 90 (LQI of link 5-7). Thus, Table I gives LQI metrics values for the WSN in Figure 4.

### E. Composite or Hybrid Metric

In this paper, we define the composite metric (hybrid) as follows:

$$Hybrid(LQI, M_i) = \rho * LQI + (1 - \rho) * Sc(M_i) \qquad (2)$$

$$Hybrid(M_i, M_j) = \rho * Sc(M_i) + (1 - \rho) * Sc(M_j) \qquad (3)$$

where $Sc(M_i)$ is a scale function, which returns remaining energy values comparable to LQI values. This help avoiding the composite metric to be strongly influenced by the $M_i$ component in (2):

$$Sc(M_i) = \alpha + \frac{\beta * \log(1 + (M_i - M_{i,min}))}{\log(1 + M_{i,max})} \qquad (4)$$

Where $M_i$ is a metric, $M_{i,min}$ (resp. $M_{i,max}$) is the minimum (resp. maximum) value of $M_i$. If $M_i$ is the remaining energy of the node, $M_{i,min}$ represents the value under which, the sensor is considered dead (battery depletion); while $M_{i,max}$ is the initial energy value of a new battery. $\alpha = 50$, $\beta = 255$.

Like the LQI metrics definition, we can also define AvgHybrid, MaxHybrid and MinHybrid metrics depending on whether, we are respectively considering AvgLQI, MaxLQI and MinLQI as defined in Table I.

## IV. ROUTING MECHANISMS

### A. Simple Routing

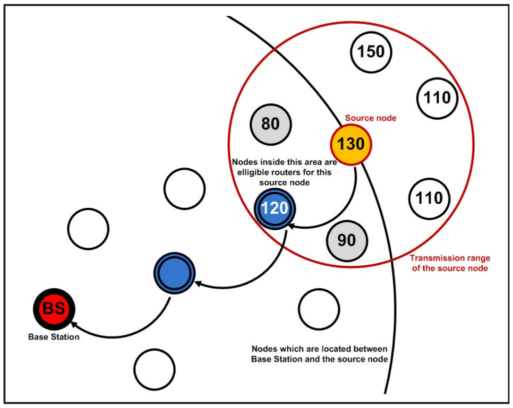

Fig. 5. Simple Routing: Nodes with their Metric Values

In the simple routing mechanism, each sensor $S_i$ selects an achtophorous node which matches the highest metric in its vicinity and located between the sensor $S_i$ and the BS. For each given sensor, a unique achtophorous node plays the next hop role for all its packets until the next election (see Figure 5).

### B. Round-Robin Routing

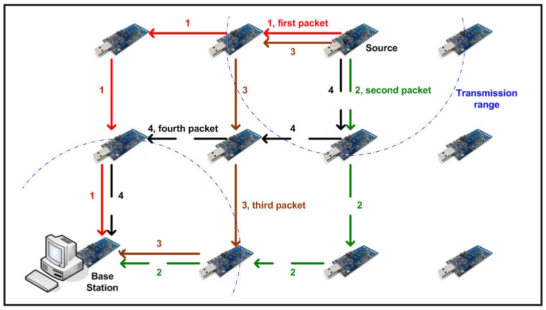

Fig. 6. Round-Robin Routing: Multiple routes from each source

In the round-robin routing, each source node has to elect two or more achtophorous nodes. The source node sends data in round-robin fashion, simply taking turns which achtophorous node it routes each packet out (see Figure 6). This routing mechanism is a per-packet load balancing routing which gives most even distribution across next achtophorous nodes.

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This per-packet load balancing method means that packets in a particular connection or flow arrive at their destination out of sequence. This does not cause a problem for most applications, but it can cause problems for the increasingly popular streaming media, both video and audio. In this paper, only data packets are concerned within cold chain monitoring application for which the packet sequence order is not an issue.

### C. Weighted Round-Robin Routing (W2R routing)

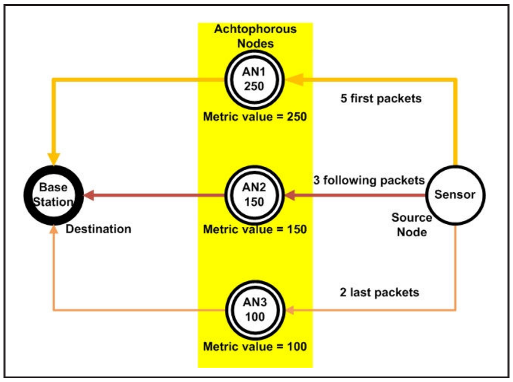

Fig. 7. Weighted round-robin routing (W2R routing)

TABLE II
WEIGHT OF ACHTOPHOROUS NODES IN FIGURE 7

| *Achtophorous Node* | *Metric* | *Weight* | *Load handled* |
|---|---|---|---|
| $AN1$ | 250 | 0.5 | 50% |
| $AN2$ | 150 | 0.3 | 30% |
| $AN3$ | 100 | 0.2 | 20% |

The weighted round-robin routing (W2R routing) is a load balancing mechanism that involves assigning a weight to each achtophorous node. Weights are proportional to metric values. In the W2R routing, each achtophorous node is assigned a value that signifies, relative to the other achtophorous nodes in the routing table, how the source node performs. The weight determines how many more (or less) packets are sent to that achtophorous node, compared to the other achtophorous nodes (see Figure 7). The W2R routing is one way addressing some shortcomings. In particular, it provides a clean and effective way by focusing on fairly distributing the load amongst available achtophorous nodes, versus attempting to equally distribute data packets.

For example, in Figure 7, the source node routes $50\%$ of its packets through $AN1$, $30\%$ through $AN2$ and $20\%$ through $AN3$. If the BS is not located within the transmission range of an achtophorous node, this one should apply the same mechanism to retransmit the packet towards the BS.

The weighted round-robin routing mechanism is computed as described in the simple Algorithm 1 which is computed each time a source node has to send a packet. The achtophorous nodes, each with its respective $weight$, are listed in the routing table of each source node in an ordered manner such that the first achtophorous node matches the highest $weight$ as shown in Figure 7. For each source node, the $window$ interval is the constant length of each stream of consecutive packets to transmit. The $weight$ of each achtophorous node is converted as an integer value based on the $window$ interval parameter. For example, in Figure 7, $window = 10$ consecutive packets, and $weight(AN1) = 5$. The $use(AN)$ function returns the number of times the current achtophorous node $AN$ is used during the $window$ interval whereas $packet\_idx$ is the index of the current packet during the $window$ interval.

```
Algorithm 1 : Weighted Round Robin (W2R) Routing
Require: $packet\_idx$, $window$, $AN$, $weight$, $use$
if $packet\_idx < window$ then
    if $use(AN) < weight(AN)$ then
        $Send\_packet\_to(AN)$
        $use(AN) \leftarrow use(AN) + 1$
        $packet\_idx \leftarrow packet\_idx + 1$
    else
        $use(AN) \leftarrow 0$
        $AN \leftarrow Next().achtophorous\_node$
        $\# The\ next()\ of\ the\ last\ AN\ is\ the\ first\ AN$
        $Send\_packet\_to(AN)$
        $use(AN) \leftarrow 1$
        $packet\_idx \leftarrow packet\_idx + 1$
    end if
else
    for $each\ achtophorous\_node\ AN$ do
        $use(AN) \leftarrow 0$
    end for
    $AN \leftarrow First().achtophorous\_node$
    $Send\_packet\_to(AN)$
    $use(AN) \leftarrow 1$
    $packet\_idx \leftarrow 1$
end if
return $packet\_idx$, $AN$, $use$
```

## V. L2RP: THE LINK RELIABILITY BASED ROUTING PROTOCOL

The proposed (L2RP) routing protocol (see Figure 8) consists for a sensor having an empty routing table to elect one next hop router (case of simple routing) or more achtophorous nodes (load balancing routings) amongst its neighbors according to the following:

- **Initial step** : all sensors empty their routing tables.
- The sensors located in the vicinity (transmission range) of the BS send their data directly to it.
- A sensor, located outside of the vicinity of the BS, inspects its routing table:
    - If its routing table is not empty, it checks if the link with the next hop is reliable or not. If the link is unreliable, based on the LQI value, then :

    * Case of simple routing mechanism: it sends a "ROUTE REQUEST" to its neighbors.
    * Case of load-balancing routing: it chooses an alternate route and then checks again if the link with this next hop is reliable or not. If no link with achtophorous nodes listed in its routing table is reliable, then it erases the routing table and it sends a new "ROUTE REQUEST" to its neighbors.
  - If its routing table is empty, it also sends a "ROUTE REQUEST" to its neighbors.
  - Each neighbor, located between the BS and the sensor having sent the "ROUTE REQUEST", computes its own waiting time which is inversely proportional to its metric value. We use the Wait and See protocol (WaS), as in [2], where the only sensor having the highest metric sends a "ROUTE REPLY" to the requester node. The other neighbors simply ignore the "ROUTE REQUEST" avoiding useless "ROUTE REPLY" packets. In the case of a load balancing routing, the number (ANs) of achtophorous nodes is a known parameter in the initialization phase of the network. This parameter is used by the WaS protocol that allows ANs sensors having highest metrics in succession to answer to the requester node, and then be elected, for this node, as achtophorous nodes.
  - Upon reception of the "ROUTE REPLY" packet, the requester node updates its routing table, which remains valid until the next election. In the case of weighted round-robin routing, each "ROUTE REPLY" packet contains the metric value of the answering node, which allows the requester node to calculate weights associated with each achtophorous nodes.
  - At the end of the current cycle, sensors reset their routing tables and go back to the initial step of the next cycle.

Upon receipt of a "ROUTE REQUEST" packet, a sensor $S_i$ computes its own waiting time according to the following formula:

$$Timer(S_i) = \tau + \frac{\zeta}{1 + \log(1 + M_i + \frac{id(S_i)}{\Gamma} * M_i)} \qquad (5)$$

where $M_i$ is the metric value of the sensor $S_i$. $\tau$ and $\zeta$ are nonzero positive constants. $\Gamma$ is a constant which is more large than the network size ($\Gamma = 10^6$, for example). This timer function avoids collisions between nodes having the same metric value. Since $M_i \geq 0$, if $M_i = 0$ then the sensor $S_i$ can not be an achatophorous node.

As we can see, in this protocol the source node uses the link quality indicator (LQI) to check if the link it forms with the nominated achtophorous node is reliable or not. This helps avoiding to send the packet to an achtophorous with which it forms a link of poor quality which could lead to packet loss.

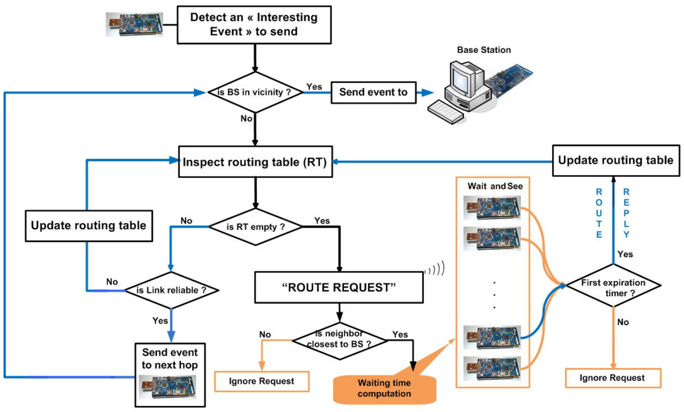

Fig. 8. The Link Reliability based Routing Protocol (L2RP) flowchart

## VI. PERFORMANCE CRITERIA

### A. Average Ratio of the Remaining Energy

The average ratio of the remaining energy is the ratio of the average remaining energy on the average of initial energy. Multiplied by hundred, this value represents the average battery life of sensors, in terms of percentage. The higher this value is, the more energy-efficient the routing protocol is.

### B. Average Path Lengths

The average path lengths are calculated in terms of the number of hops traversed by packets before reaching the BS. A large value reflects participation of many sensors in the effort due to the routing, which may increase the overall energy consumption. A good routing protocol is recognized in this performance criterion by a relatively low value. Conversely, too small path length may lead to bad quality link.

### C. LIF: Load Imbalance Factor

The load imbalance factor (LIF) is defined as the root of the squared coefficient of variation of the relative remaining energy. This shows the energy spent by communications:

$$LIF = \sqrt{\frac{Var(E_R^i)}{\overline{E_R}^2}} \qquad (6)$$

where $E_R^i$ is the ratio of the remaining energy of sensor $S_i$; and $\overline{E_R}$ is the average ratio of the remaining energy.

### D. Network Lifetime

In this paper, we define the network lifetime as the average number of packets routed until the first time a sensor run out of battery. This could also result in network capacity. We focus on the first battery depletion, which means the instant the network stops fulfilling totally its role, because it leads to packet losses. An ideal network is a network where all packets sent by source nodes are actually transmitted to the recipient (BS). The earlier the first packet loss happened, the more ineffective the routing protocol is.

### *E. Average Percentage of Lost Packets*

Beyond the first time a battery depletion is experienced by the network, a high percentage of packet losses might reflect an unreliable network whose routing protocol is less effective.

## VII. SIMULATION MODEL

### *A. Energy Consumption Model*

Let $E_{Tx}(k,d)$ the energy [37][38] consumed to transmit k bits message over a distance d :

$$E_{Tx}(k,d) = E_{elec} * k + \varepsilon_{amp} * k * d^2 \tag{7}$$

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

$$E_{Rx}(k,d) = E_{Rx-elec}(k) = E_{elec} * k \tag{8}$$

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

### *B. Network Deployment and simulation parameters*

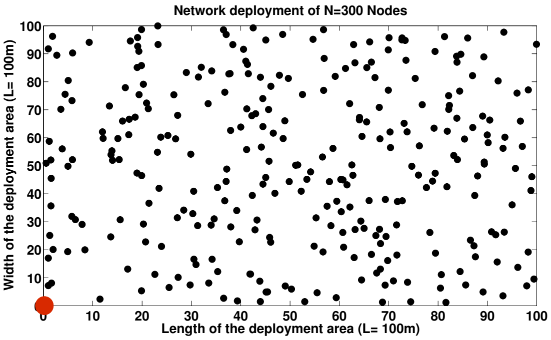

Fig. 9. Netwrok Deployment of N=300 sensors (100m x 100m)

TABLE III
L2RP SIMULATION PARAMETERS

| Parameter | Value |
|---|---|
| **Deployment** | |
| Area Length | $L = 100m$ |
| Area Width | $l = 100m$ |
| Base Station Location | $position(SB) = (0, 0)$ |
| Radio range | $R = 20m$ |
| Network Size | $N = \{100, 200, ..., 500\}$ |
| **Poisson Parameter** | |
| Packet sent by each sensor | $\lambda = 10$ |
| **Packet Sizes (bits)** | |
| Alarms | $k_{data} = 128$ |
| L2RP "ROUTE REQUEST" | $k_{rr} = 24$ |
| L2RP "ROUTE REPLY" | $k_{rr} = 24$ |
| **L2RP Achtophorous Nodes** | |
| Number of Achtophorous Nodes | $AN = 3$ |
| Window interval for W2R | $window = 10$ |
| **LQI parameters** | |
| Treshold for MinLQI | $LQI \geq 100$ |
| Link Reliability (L2RP) | $LQI \geq 70$ |
| **Energy** | |
| Initiale Energy Level | $E_0 = (1.404 * 10^5 - \varepsilon)\mu J$<br>$\varepsilon = random(0, 1) * 10^2 \mu J$ |
| Minimum Energy Level | $E_{min} = E_0 * 0.05$ |

In the simulation model N nodes are randomly (according to a uniform distribution) deployed over an area of length L=100m, and width l=100m (see Figure 9). The BS is located at the (0,0) position. Each node generates a sequence of "interesting events", which are sensed data over the temperature threshold $T_{min}$, following the Poisson process of parameter $\lambda = 10$. For simulation scenarios, the size of each data packet is set to $k_{data} = 128 bits$, and the "ROUTE REQUEST" and "ROUTE REPLY" packets of the L2RP protocol have a size of $k_{rr} = 24 bits$. Each node knows its position and its energy level. The initial energy amount of each node is set to $E_0 = (1.5 * 10^5 - \varepsilon)\mu J$, $\varepsilon = rand(0, 1) * 10^2$. A node battery exhaustion is experienced when the remaining energy level of the node is under the given treshold $E_{min} = E_0 * 0.05$. All nodes, including the BS, have same transmission range (R = 20m). The main simulation parameters are listed in Table III.

### *C. LQI Model for Simulation Purposes*

The WSN can be modelled 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 neighbourhood of the node $x$. At each given time $t$, 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 $\ell(x, y, t) > 0$. For all other nodes $z \in V \setminus \mathcal{N}_1(x)$, $\ell(x, z, t) = 0$. Let $\nu$ be a bijective function defined in $V$ which is a totally ordered set. The $\nu$ function is defined as follows:

$$\forall\, x \in V, \;\; \nu(x) = (f(x), id(x)) \tag{9}$$

where $f(x)$ is the function which returns the metric value of $x$, and $id(x)$ returns the address of the node $x$. The total ordering in $V$ is defined as follows:

$$\begin{aligned} \forall x \in V, \;\; \nu(x) > \nu(y) \iff (f(x) > f(y)) \\ or \quad (f(x) = f(y) \quad and \quad id(x) > id(y)) \end{aligned} \tag{10}$$

After the WSN deployment in the warehouse, the BS initially broadcasts a message containing its position. This information is then retransmitted to all sensors in the network. In this phase, each node knows its degree of connectivity. 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:

$$\ell(x, y, t) = f(x, y, t) * g(x, y) \tag{11}$$

$$f(x, y, t) = 1 - Pr\,[\ell ink(x, y, t) = Unreliable] \tag{12}$$

$$g(x, y) = \alpha + \frac{\beta * \log(1 + (\gamma(x, y) - \gamma_{min}(x)))}{\log(1 + \gamma_{max}(x))} \tag{13}$$

$$\gamma_(x, y) = \frac{1}{d(x, y)} \tag{14}$$

$$\gamma_{min}(x) = \min_{y \in \mathcal{N}_1(x)} \gamma(x, y) \tag{15}$$

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$$\gamma_{max}(x) = \max_{y \in \mathcal{N}_1(x)} \gamma(x, y) \tag{16}$$

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 (12), $Pr\left[\ell ink(x, y, t) = Unreliable\right]$ 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 behaviour of our L2RP protocol with respect to the unrelibility aspect of the wireless links.

The choice of this model, formula (13) similarly to the scale function $Sc$ defined in the composite metric, is guided by experimental results shown in [39] and [10] 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 (15) and (16). Hence, the model allows to take into account asymetrical aspects of the wireless links.

For moteiv′s Tmote Sky [4] sensors equipped with chipcon′s CC2420 [7], the LQI values range from 50 to 110. Even so, we stick with the ZigBee standard [5][6] because some manufacturers, such as Sun-SPOT [35] and WiEye [36], 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. $Pr\left[\ell ink(x, y, t) = Unreliable\right] = 1$.

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

## VIII. SIMULATION RESULTS

Simulations, using Matlab, are run for a network size ranging from 100 to 500 nodes. The performance results presented here are obtained by averaging the results for 50 different simulations for each scenario comparing the route selection criteria. In each scenario where the three routing mechanisms are compared, 25 different simulations were run. For each simulation, a new random node layout is used.

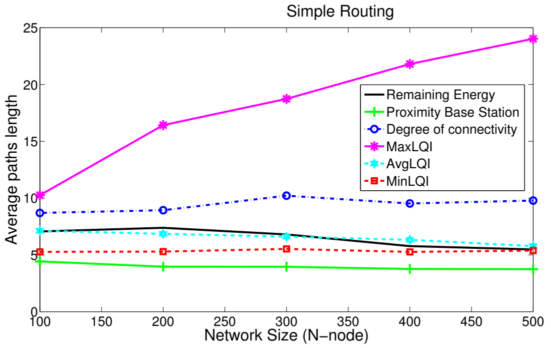
In all simulation results presented below, $\rho = 0.5$ for the composite metric as defined in formulas (2) and (3). If it's not specified, the number $ANs$ of Achtophorous Nodes is set to $ANs = 3$ for each load balancing mechanism.

In all simulation scenarios, except those in Section VIII-H, links are considered reliable, i.e.:

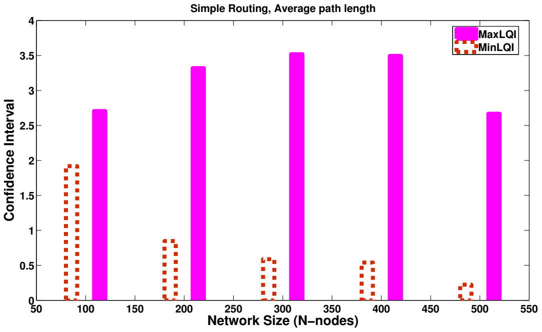
$$\forall t,\ \forall x \in V,\ Pr\left[\ell ink(x, y, t) = Unreliable\right] = 0\ , \forall y \in \mathcal{N}_1(x).$$

For some results, the related confidence intervals for a confidence coefficient of 95% are computed as detailed in the section 3.3 of [40].

### A. Average Path Length



(a) The average path length (Simple routing)



(b) Confidence Interval for MaxLQI and MinLQI metrics

Fig. 10. Average path length: Comparison of metrics in simple routing mechanism (a); and the related confidence interval for a confidence coefficient of 95% (b)

The Figure 10(a) shows the average path length for the simple routing; while the Figure 11(a) compares the average path length related to the "Proximity with respect to the BS" metric when it is used in the simple and load balancing mechanisms.

This result shows that routes are longer for MaxLQI and degree of connectivity metrics. The remaining energy, AvgLQI, MinLQI and "Proximity with respect to the BS" metrics have better average path lengths.

The Figure 10(a) shows, in the case of simple routing mechanism, the average path lengths in terms of the average number of hops obtained with the different studied metrics when the node density is increasing in the deployment area. This result shows that routes are longer for the MaxLQI and degree of connectivity metrics. The remaining energy, AvgLQI, MinLQI and "Proximity with respect to the BS" metrics have better average path lengths. The gap is more important for the MaxLQI metric with respect to the other metrics. Moreover, for MaxLQI, the average number of hops is a monotonically increasing function of the network density. This reflects the fact that the routing according to the metric

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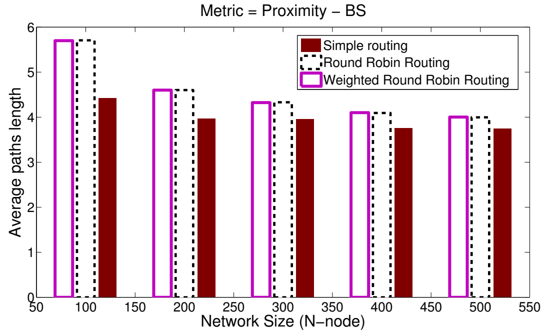
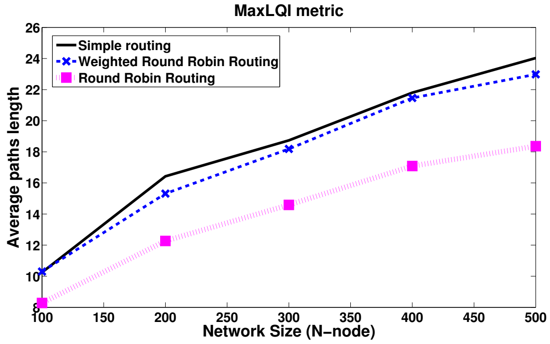


(a) The average path length (Proximity-BS)



(b) The average path length (MaxLQI)

Fig. 11. Average path length: Comparison of the three routing mechanisms with the Proximity-BS (a) and MaxLQI (b) metrics

MaxLQI consists of choosing as an achtophorous node the node having the best link quality with the source node. In the absence of obstacles and other phenomena like interferences, the best link quality is determined by the shortest distance separating a node from the source node. So, routing according to the MaxLQI metric is equivalent to a multihop "step by step" routing which is characterized by a great number of hops due to small distances separating each source node and its achtophorous node.

When the network density is increasing, the distances separating sensors decrease. Thus, the distances separating each source node and its achtophorous node also decrease, as well. So, from any source node towards the base station, the number of hops of each sent packet become increasingly high when the MaxLQI is used. By multiplying the number of hops, in this manner, the sensor network could not claim to have a good performance. This result explains the low performance of the MultiHopLQI routing algorithm which is used today in many TinyOS based empirical WSN analysis. Indeed, MultiHopLQI uses the LQI metric as defined in the ZigBee standard [5][6], that is to say the MaxLQI metric.

Conversely, the Proximity-BS and MinLQI metric have the lowest average path lengths (see Figure. 10(a)). For any given source node, the selected Proximity-BS based achtophorous node matches the farthest neighboring node towards the Base Station. Therefore, the routing according to the Proximity-BS metric is equivalent to the shortest geographical path routing. Accordingly, packets are transmitted from the source node to the base station requiring the minimum number of hops. This result (see Figure. 10(a)) is also interesting for the MinLQI metric. Indeed, this metric promotes the use of the links of intermediate quality. Links of good quality are synonymous with the nearest nodes multiplying the number of hops, whereas the links of poor quality stand for lot of packet losses. This explain why MinLQI is a good metric.

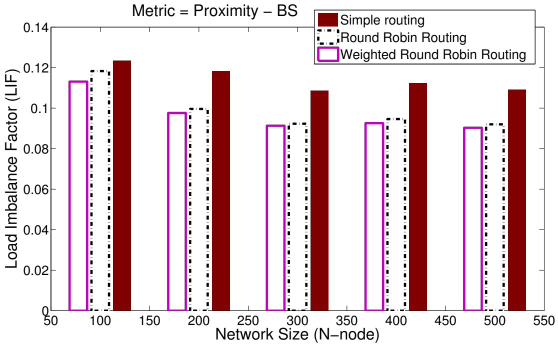
For the Proximity-BS metric, the load balancing mechanisms have the effect of increasing the average path lengths which is almost the same average for the weighted round robin routing and the round robin one (see Figure 11(a)). In the case of load balancing mechanisms, each sensor has in its routing table several achtophorous nodes of which only one exactly corresponds to the achtophorous node used by the simple routing. The other achtophorous nodes are necessarily more distant from the base station. So, the average path lengths slightly increase for load balancing mechanisms with respect to the simple routing using the Proximity-BS metric (see Figure 11(a)). For any given source node, the selected achtophorous nodes are identical for both load balancing mechanisms, their use only differs by the weight introduced in the weighted round robin routing. This leads to an average number of hops almost identical (see Figure 11(a)).

Unlike the Proximity-BS and MinLQI metrics , the MaxLQI one has an average path lengths which is reduced by the load balancing mechanisms (see Figure 11(b)). In this case, the weighted round robin routing mechanism has an average number of hops closer to the one of the simple routing mechanism than the round-robin one. Indeed in the case of W2R, the achtophorous node which forms the better link quality (MaxLQI) is also the one which has the highest weight. Thus, depending on the weight value, the sensors choose to send their packets more frequently to that achtophorous node. Therefore, W2R leads to an average number of hops closer to the one of the simple routing mechanism (see Figure 11(b)).

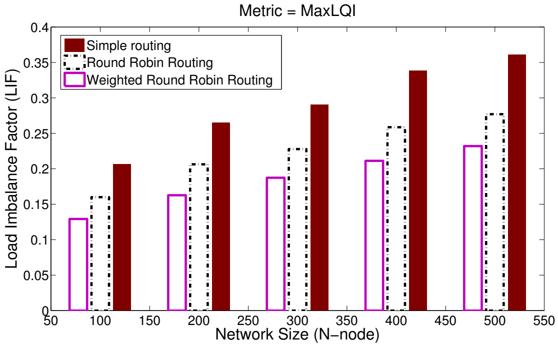
### *B. LIF: Load Imbalance Factor*

The Figure 12(a) shows the LIF when the "Proximity with respect to the BS" is used as metric. It displays results for the simple routing and load balancing mechanisms. The Figure 12(b) for MaxLQI and the Figure 12(c) for MinLQI also display the LIF for the three routing mechanisms.

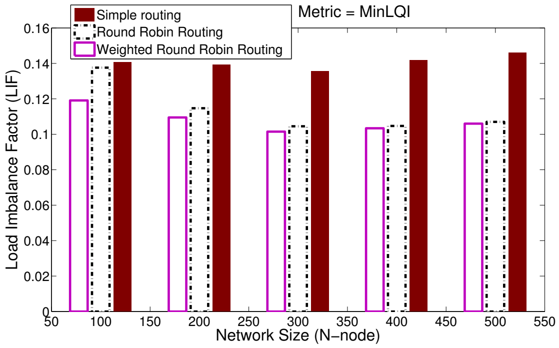
The lowest LIF value indicates the best evenly distribution of the energy consumption between nodes. It would be redundant to say that the load balancing mechanisms (round robin and W2R) help evenly balancing the load. That is to say that the average LIF values are lower for load balancing mechanisms compared to the simple routing, whatever the chosen metric (see Figure 12(a), 12(b) and 12(c)). But the gap is more important for MaxLQI than other metrics.



(a) Proximity-BS



(b) MaxLQI



(c) MinLQI

Fig. 12. Load Imbalance Factor: Proximity-BS (a), MaxLQI (b) and MinLQI (c)

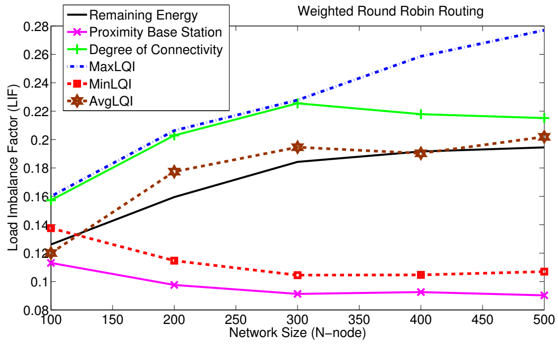


Fig. 13. Load Imbalance Factor: Comparison of different metrics in the Weighted Round Robin Routing, i.e. W2R Routing, mechanism

Moreover, when the network density is increasing, the difference between round robin and W2R tend to vanish for the Proximity-BS and for the MinLQI (see Figure 12(a) and 12(c)). For these two metrics, it would be more suitable in dense wireless sensor networks to use the round robin mechanism than the W2R one. Therefore, in doing so, one saves the power required, mainly by the processor, for the achtophorous weight computations (see Figure 7 and Table II).

These results confirm that load balancing mechanisms help in the distribution of the load across the nodes, because whatever the metric used: the W2R routing produces lower LIF than the round-robin routing which is followed by the simple routing (see Figure 12(a),12(b),12(c)).

As for the Figure 13, it compares the average LIF of different metrics in the W2R routing. The "Proximity with respect to the BS" and MinLQI metrics produce lower LIF values (see Figure 13). The remaining energy metric has an intermediate LIF, while the degree of connectivity and MaxLQI metrics tend to imbalance the energy consumption on the network: some sensors exhaust their batteries while others have a little participation in packet routings towards the BS. This negative phenomenon is much more important for the MaxLQI metric when the network size is increasing (see Figure 12(b) and Figure 13).

This reflects the fact that the degree of connectivity and MaxLQI metrics are the ones for which packets arrive at the Base Station by routes using the largest number of hops as shown in Figure 10(a) and explained in the last section. Thus, along each route, the WSN experiences more retransmissions and then more energy wastage due to the effects of overhead, latency and overhearing phenomena which are more important when the average number of hops is increasing.

### C. Average Percentage of Packet Losses

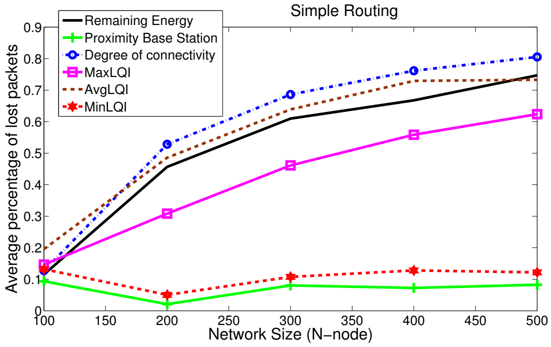


Fig. 14. Average percentage of lost packets: Comparison of the different metrics in the Simple Routing mechanism

The Figure 14 displays, for each metric, the average percentage of packet losses experienced by the network when the simple routing is run. The three routing mechanisms are

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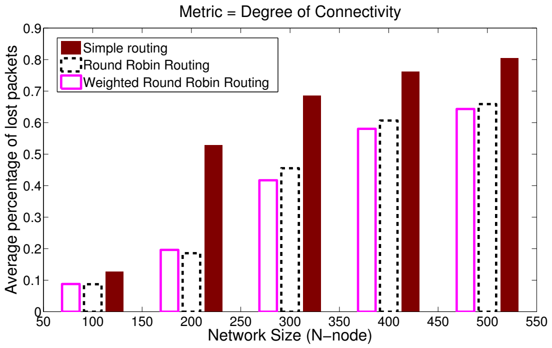


Fig. 15. Average percentage of lost packets: Comparison of the three routing mechanisms with the Degree of connectivity metric

compared (see Figure 15) using the degree of connectivity metric.

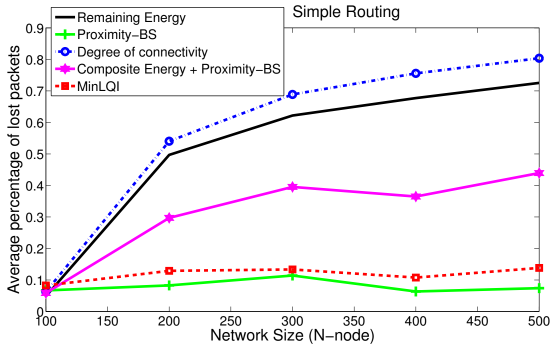
Generally, the loss percentage is quite low. This reflects the fact that, in L2RP, losses are mainly due to the node battery exhaustion. The first result (see Figure 14) compares the different criteria in the mechanism of simple routing. Here again, best results are produced by MinLQI and "Proximity with respect to the BS" metrics. MaxLQI has an intermediate average percentage of packet losses, while the remaining energy and degree of connectivity metrics have higher percentages. For the Proximity-BS metric this result is easy to understand, because according to the previous results (Figure. 10(a)), Proximity-BS is the metric which produces the shortest path lengths. Accordingly, as the overhearing phenomenon and the overhead induced by routing are reduced when the number of hops is minimal, then the node battery exhaustion occurs later (in time) leading to a low loss percentage for the metric Proximity-BS.

Conversely, the degree of connectivity metric has the highest percentage of packet losses (see Figure 14). By choosing to route packets according to this metric, any given sensor which has data to transmit chooses its achtophorous node, in simple routing, as its neighbor which has the highest number of neighbors. Therefore whenever an achtophorous node is requested to route a packet, the overhearing phenomenon causes more energy consumption which leads to a greater packet loss percentage.

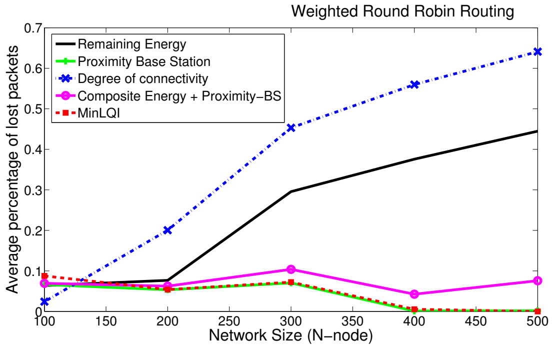
For all metrics, load balancing significantly reduces the average percentage of packet losses (see Figure 15). Load balancing mechanisms produce lower packet losses than the simple routing; differences are more important when load balancing is run with the degree of connectivity metric, the remaining energy metric or the MaxLQI metric.

Indeed, for the degree of connectivity metric of which the overhearing phenomenon is the most important, Load balancing requires the selection of different achtophorous nodes for each source node. So, in the routing table there is exactly one node which has the highest number of neighbors: this the one used by the simple routing mechanism. Then, in load balancing when the other achtophorous nodes with less neighbors are used, this helps reducing the overhearing phenomenon. This justifies why load balancing reduces the percentage of packet losses compared to simple routing which always requires the highest degree of connectivity as achtophorous node (see Figure 15).

## *D. Composite or Hybrid Metric*



(a) Simple routing



(b) W2R Routing

Fig. 16. Average percentage of lost packets: Comparison of different metrics including the hybrid metric (remaining energy level + Proximity-BS) in Simple routing (a) and W2R Routing (b)

The Figure 16(a) (simple routing) and the Figure 16(b) (W2R routing) display the average percentage of packet losses including the hybrid metric which is a combination of the remaining energy metric and the "Proximity with respect to the BS" metric.

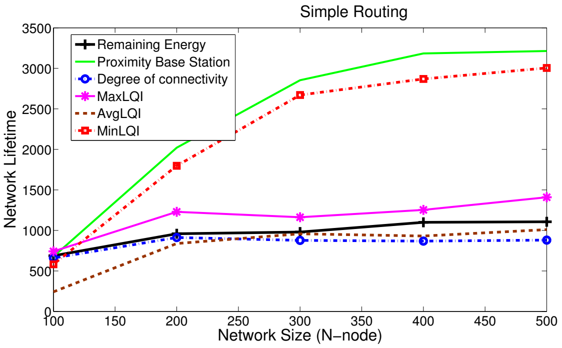
These results show that the hybrid metric composed of $50\%$ of the remaining energy and $50\%$ of "Proximity with respect to the BS" (i.e. $\rho = 0.5$ in Formula (3)) is a very good metric. It has a percentage of packet losses which is relatively low, especially when it is used with load balancing mechanisms. As we can see, there are fewer lost packets when the simple routing is run with the MinLQI metric than the W2R routing run with the remaining energy metric, MaxLQI or the degree of connectivity metric (see Figure 16(a) and Figure 16(b)).

These results show that compared to the "remaining energy level" metric, the hybrid metric helps mitigating losses particularly in load balancing (W2R Routing) where the average packet loss percentage is less than $0.1\%$ for this metric.

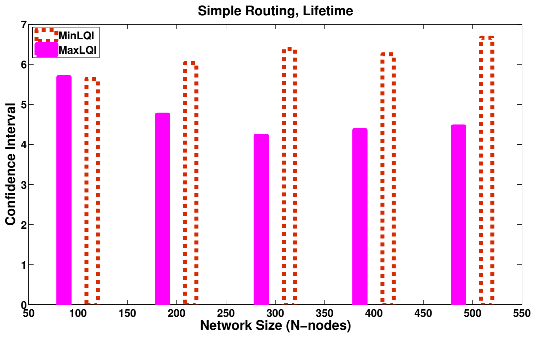
This kind of metric is very interesting to consider because depending on the specific WSN application purposes, it may be useful to consider several criteria for selecting routes by computing a single hybrid metric. In this result, it is more beneficial to route jointly depending on the distance and the remaining energy than to route only along with the remaining energy criterion. This reflects the fact that the "remaining energy level" criterion is not a good metric for route selection. Because in our simulation scenario (see Table III) each node is deployed with an initial energy level $E_0$ which is randomly and slightly lower than a reference value $E_0 = (1.404 * 10^5 - \varepsilon)\mu J$ with $\varepsilon = random(0,1) * 10^2 \mu J$. This scenario is very realistic, because even if the AA batteries powering the sensors are new, they also have slightly different energy levels in real world scenario.

Although the average percentage of packet losses is generally too low, the load balancing helps reducing the packet loss percentage for the hybrid metric similarly to all other studied metrics.

### *E. Average Network Lifetime*

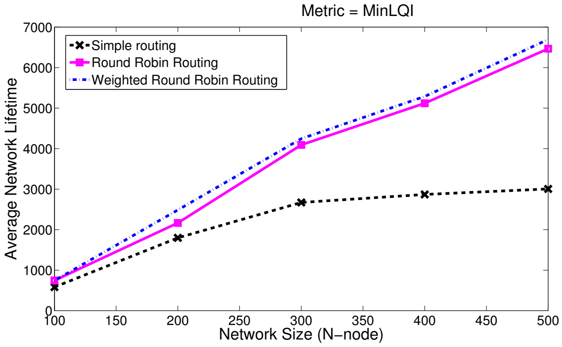


(a) Average network lifetime (Simple Routing)

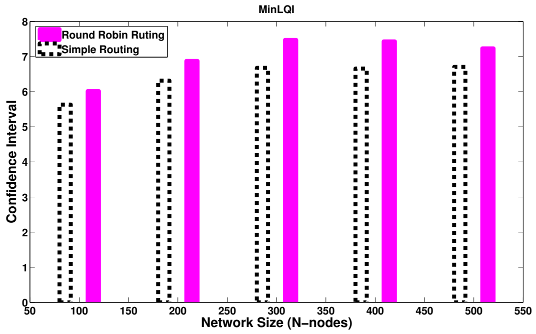


(b) Confidence Interval for MaxLQI and MinLQI metrics

Fig. 17. Average network lifetime: Comparison of different metrics in the simple routing mechanism (a); and the related confidence interval for a confidence coefficient of $95\%$ (b)



(a) Average network lifetime (MinLQI)



(b) Confidence Interval for simple and round robin routings

Fig. 18. Average network lifetime: Comparison of the three routing mechanisms using the MinLQI metric (a); and the related confidence interval for a confidence coefficient of $95\%$ (b)

The Figure 17(a) displays the average network lifetime for the simple routing. The Figure 18(a) shows the average network lifetime when MinLQI is used in each routing mechanism.

Firstly, these results show that more dense networks have better lifetime. The MinLQI and "Proximity with respect to the BS" metrics produce better network lifetime. MaxLQI is better than the remaining energy metric which is followed by the degree of connectivity metric (see Figure 17(a)). Load balancing mechanisms significantly increase the average network lifetime which is more large than the one of the simple routing with more differences for MinLQI (see Figure 18(a)) and "Proximity with respect to the BS" metrics.

The time of first packet loss occurs earlier for the degree of connectivity metric. As we explained in the previous sections, this result is also caused by the overhearing phenomenon of which effects are more important for the degree of connectivity metric with respect to other metrics. The Proximity-BS metric improves the network lifetime by minimizing the number of hops (see Figure 17(a)).

Compared to the simple routing, the load balancing mechanisms (see Figure 18(a)) significantly increase the WSN lifetime. However, even if the weighted round robin routing leads to a better WSN lifetime than the round robin routing, the gap between the two load balancing mechanisms is not significant for the MinLQI metric (see Figure 18(a)).

By rotating the achtophorous node this helps splitting the load among different sensors. So, load balancing helps delaying the moment of the first node battery depletion of and therefore extending the lifetime of the network: Load balancing adds lifetime benefits to the WSN.

### *F. Average Ratio of the Remaining Energy*

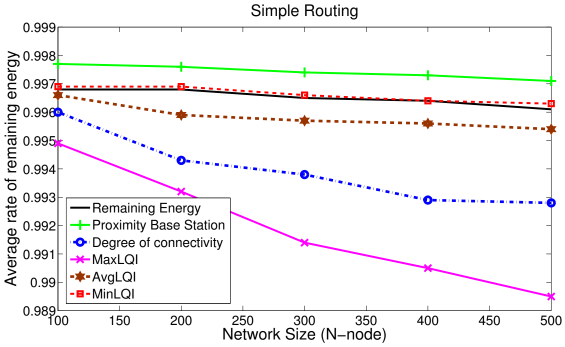


Fig. 19. The average ratio of the remaining energy: Comparison of the different metrics in the Simple Routing mechanism, after one cycle of which all sensors had sent their alarms towards the Base Station.

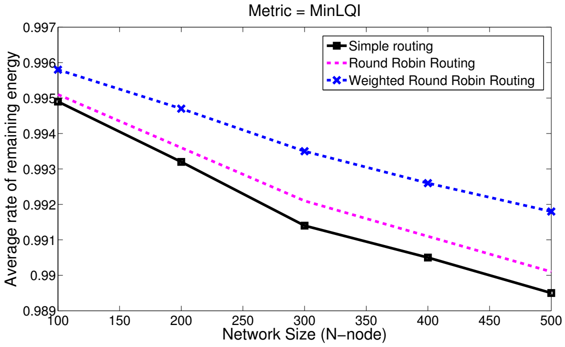


Fig. 20. The average ratio of the remaining energy: Comparison of the three routing mechanism with the MaxLQI metric, after one cycle of which all sensors had sent their alarms towards the Base Station.

The figures (see Figure 19 and Figure 20) show, depending on network density, the evolution of the average remaining energy after a complete cycle. The cycle is constituted by: the network deployment, the detection of alarms and the data routing towards the base station where each source node uses L2RP to build its routing table. The cycle ends when all nodes have sent their alarms.

The degree of connectivity and MaxLQI metrics are the least energy efficient metrics (see Figure 19). In contrast, Proximity-BS and MinLQI are the metrics that ensure better energy efficiency.

The weighted round-robin routing (W2R) leads to less energy consumption than the round-robin routing which is better than the simple routing whatever the metrics used. The Figure 20 shows the result for the MaxLQI metric.

In summary, these results are natural consequences of the previous ones. Indeed, for the MaxLQI metric of which the average number of hops (average path length) is high, the energy consumption is also large because of the increasingly overhearing, latency, and overhead phenomena.

### *G. Impacts of Increasing the Number of Achtophorous Nodes*

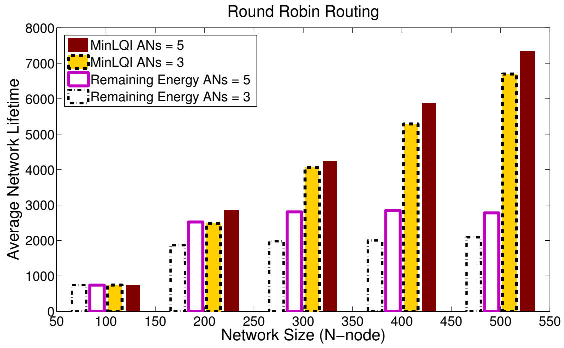


Fig. 21. Impacts of increasing the number of achtophorous nodes on the average network lifetime for the round-robin routing mechanism.

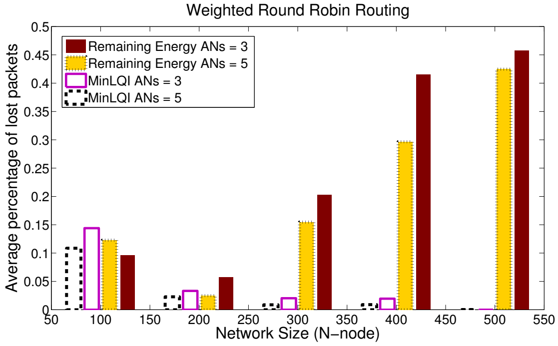


Fig. 22. Impacts of increasing the number of achtophorous nodes on the average percentage of packet losses for the W2R Routing mechanism

The Figure 21 shows the influence of the number (ANs) of the achtophorous nodes on the network lifetime performance criterion by comparing the results for ANs = 3 and ANs = 5, when the remaining energy and MinLQI metrics are combined with the round-robin routing.

The Figure 22 shows the influence of increasing the number (ANs) of the achtophorous nodes on the average percentage of lost packets by comparing results for ANs = 3 and ANs = 5, when the W2R routing is run with the remaining energy and MinLQI metrics.

These two results (see Figure 21 and Figure 22) show that the average percentage of lost packets decreases for the MinLQI metric. The network lifetime increases for both metrics when the number of achtophorous nodes varies from

3 to 5. This is not obvious to predict, because increasing the number of achtophorous nodes might increase the risk of using low-energy sensors in routing process, which could cause more packet losses.

From a given number of achtophorous nodes, the result should be reversed. Nevertheless, until the value $AN = 5$, it remains within reasonable limits for a cold chain monitoring application.

### *H. Impacts of the Unreliability of 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 the wireless links. In this section we take into account such a phenomenon. At any given time $t$, for a sensor $S_i$, its unreliable links ($Pr\left[\ell(i,j,t) = Unreliable\right] = 1$ in Formula (12)) with some neighbors are modeled by the Poisson process of parameter $\gamma(S_i,t)$ calculated as follows:

$$\gamma(S_i,t) = \frac{\mu}{\delta(S_i)} \tag{17}$$

where $\delta(S_i)$ is the number of nodes located between the node $S_i$ and the BS. If $\delta(S_i) = 0$, then the node $S_i$ has no elligible achtophorous node.

At any given time $t$, for each sensor $S_i$, $\gamma(S_i,t)$ is too small, then the Poisson process returns a series $\mathcal{T}_i$ of integers $\mathcal{T}_i$, in which nonzero values $\mathcal{T}_i[j]$ denote the unreliable links formed by $S_i$ with some of its neighbours $S_j$, i.e. $Pr\left[\ell(i,j,t) = Unreliable\right] = 1$ in Formula (12).

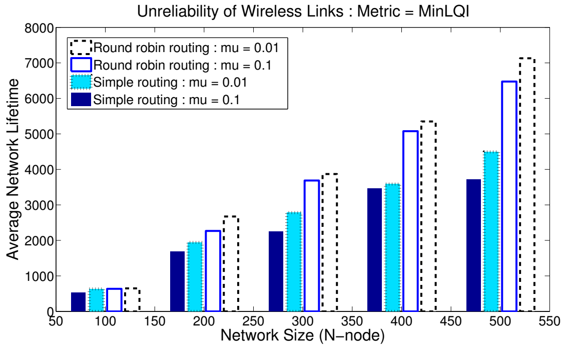


Fig. 23. Impacts of the unreliability of the wireless links on the average network lifetime (MinLQI, $\mu = 0.01$ and $\mu = 0.1$) for both simple and round robin routing mechanisms

The Figure 23 shows the effect of the unreliabilities of the wireless links on the WSN lifetime by comparing results for $\mu = 0.01$ (low unreliability) and $\mu = 0.1$ (high unreliability), when the MinLQI metric is used in the simple routing and in the round-robin routing. The Figure 24 (resp. the Figure 25) shows impacts on the average path length (resp. on the LIF) by comparing results for $\mu = 0.1$ (high unreliability), when MinLQI metric is used in the three routing mechanisms.

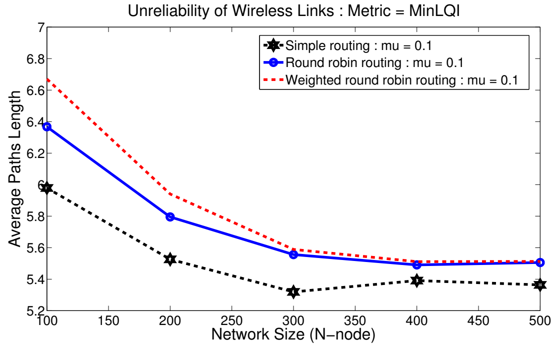


Fig. 24. Impacts of the unreliability of the wireless links on the average path length (MinLQI, $\mu = 0.1$) for the three routing mechanisms

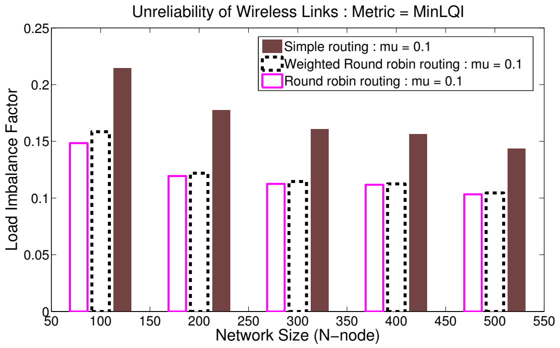


Fig. 25. Impacts of the unreliability of the wireless links on the Load Imbalance Factor (MinLQI, $\mu = 0.1$) for both simple and load balancing routings.

The first result in Figure 23, shows that the network lifetime is smaller in high unreliable WSN ($\mu = 0.1$). In this case, the load balancing also increases the network lifetime. Indeed, the round-robin routing in high unreliable WSN ($\mu = 0.1$) is much better than the simple routing in low unreliable links environment ($\mu = 0.01$), even if the simple routing produces lower average path length (see Figure 24) than load balancing mechanisms. Even in the context of high unreliable links, the load balancing routing produces better LIF than the simple routing (see Figure 25), which means that the load is more evenly shared between nodes.

This result pertained to the MinLQI metric, clearly shows that the unreliabilities of the wireless links phenomena reduce the WSN lifetime because of more retransmissions needed in such an environment. But the key point of this result relies on the fact that load balancing mechanisms also add lifetime benefits in high unreliable environment. Indeed, in the case of simple routing, a weak link between a sensor and its achtophorous node involves the sending of a new "ROUTE REQUEST" message. In contrast, for load balancing mechanisms, each sensor has several achtophorous nodes in its routing table. If a link between a sensor and its achtophorous node were to be unreliable, the source node first examines the quality of the link it forms with the next achtophorous node listed in its routing table. So, if this link is reliable, it simply sends the packet without having to request a new route.

Therefore, in load balancing mechanisms, a source node has to send a new "ROUTE REQUEST" message, if and only if all the links it forms with all the achtophorous nodes listed in its routing table were to become unreliable at the same time.

In the scenarios which do not take into account the unreliabilities of the wireless links, the L2RP protocol leads to identical routes for the two load balancing mechanisms (see Figure 11(a)). The Figure 24 shows the impacts of the unreliabilities of the wireless links on the average path lengths (number of hops) in an environment subjected to high unreliable links ($\mu = 0.1$). In this result, we observe that the routes obtained with the round robin mechanism are now different from those obtained with the weighted round robin routing (W2R) (see Figure 24). This is due by the fact that link quality parameters are very fickle and time variant and are greatly dependent on the poisson parameter $\gamma(S_i, t)$ (see Formula 17).

The Figure 25 plots, for $\mu = 0.1$, the impacts of high unreliabilities of the wireless links on the LIF criterion performance. This still confirms the effectiveness of the load balancing mechanisms in unreliable environments. Indeed, the load imbalance factor (LIF) is lower for the round robin and W2R routing compared to the simple routing. Contrary to the previous result (see Figure 12(c)), this one (see Figure 25) shows that the gap between the average LIF of the simple routing mechanism and those obtained via the load balancing routings decreases as the network density is increasing. Indeed, the unreliabilities of the wireless links become more and more important when the density of the WSN is increasing. Consequently, load balancing mechanisms gradually begin to loose some of their interest.

## IX. CONCLUSION

In this paper, we have proposed the L2RP routing protocol (Link Reliability based Routing Protocol) which takes into account the quality of the links formed by any source node with the achtophorous nodes listed in its routing table. This avoids sending data over a link disrupted, unreliable or unstable.

The L2RP protocol also includes load balancing mechanisms where the source node, based on "ROUTE REPLY" packets, is able to estimate the load sustainable by each of its achtophorous node. This property allows L2RP to avoid doing a per packet load-balancing by the source, as done in [34], where the source node sends its data without being sure of the capacity of the achtophorous node to sustain the load assigned. Thus, by doing so, L2RP helps to reduce packet losses.

Applications often have their specific objectives and constraints, so it is essential to have the choice between several possible settings when deploying a wireless sensor networks. Thus, in its design, the L2RP protocol can use any chosen metric. This allows L2RP to be able to support different applications by offering the choice of the metric which ensures the best performance in the specific context of each application.

We therefore evaluated the L2RP performance based on routing mechanisms (simple or load balancing) and then presented a comparative study of the different metrics in each routing mechanisms. This work has shown that:

- The degree of connectivity metric is the metric that leads to the highest percentage of packet losses. This metric also has the lowest network lifetime. Indeed, it is the metric which is the most sensitive to the overhearing phenomenon.

- The Proximity-BS metric provides better energy efficiency. With this metric, the alarms sent by any sensor reach the Base Station in less hops. By minimizing the number of hops, it helps in reducing energy wastefulness due to overhearing, overhead and latency.

- The LQI used as a metric by considering the best link quality (the MaxLQI metric) leads to an inefficient routing regardless of the performance criterion considered. This confirms our previous experimental results obtained in [3]. The MaxLQI metric matches the standard definition of the LQI used in the MultiHopLQI routing algorithm [8]. Indeed, this metric is characterized by a relatively high average number of hops. In the absence of obstacles and any interferences, the best link quality is often observed for the nodes which are located relatively close to each other. By multiplying the number of hops, the MaxLQI metric has the effect to increase energy wastefulness due to overhearing, overhead and latency.

- Accordingly, despite its popularity in WSN empirical analysis based on TinyOS platforms, the MultiHopLQI routing algorithm is not suitable for WSN applications, because it uses the MaxLQI metric for route selection.

- By setting a given LQI threshold, i.e. a value of acceptable LQI, and considering the lowest LQI value beyond this threshold (the MinLQI metric), we obtain an optimal LQI based metric which highly enhances the energy efficiency. As the LQI decreases when the distance between the nodes increases, the average path length is larger for MaxLQI than for MinLQI: this explains why MinLQI is more energy-efficient than MaxLQI. Then, the average percentage of packet losses is larger for MaxLQI. There is a trade-off between routes consisting of good links quality and small average path length (i.e without too many retransmissions).

- This interesting result shows that it is better for LQI based routing algorithm to promote links of intermediate quality (such as MinLQI metric) to avoid:

  - better links which are synonymous of nodes located relatively close to each other and also synonymous of higher number of hops which are responsible for excessive energy consumption;
  - bad links (low quality) which are synonymous of higher percentage of packet losses.

- The load balancing mechanisms significantly improve the routing efficiency by extending the network lifetime, while minimizing the average percentage of packet losses. The load balancing also helps evenly splitting the load on all nodes in the WSN.
- Increasing the number of achtophorous nodes improves the network performance: a low average of packet losses and a longer network lifetime.
- The composite metric, resulting of the remaining energy metric combined with the Proximity-BS metric, offers good routing performance. This metric is interesting, as each node ignores the settings of its neighbors (such as the remaining energy, the position) when selecting its achtophorous nodes.
- Since it is LQI based routing algorithm, the question that naturally arises is how L2RP behave in an environment subjected to high unrelibilities of the wireless links. Simulation results has shown that, such an environment slightly impacts the L2RP efficiency. Generally, packet loss percentage is relatively low because in L2RP a source node avoids sending data to an achtophorous node with which it forms an unreliable link at the moment it has data to transmit.

Embedded with load balancing mechanisms, L2RP adds lifetime benefits to the wireless sensor network. Nevertheless, it would be more profitable to combine L2RP with aggregation techniques like cluster formation and data aggregation in order to gain more scalability and lifetime. So, in [41] we used L2RP in a cold chain monitoring application where regular sensors send alarms to their respective clusterheads which aggregate received alarms and then forward the aggregated data towards the BS using the L2RP routing protocol. In this application L2RP is run with the weighted round robin load balancing mechanism using the "MinLQI" metric.

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