Link Quality and Local Load Balancing Routing Mechanisms in Wireless Sensor Networks

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***Abstract*—The choice of a routing protocol in a wireless sensor network (WSN) depends on the nature of the application and on its primary mission. Lot of works addressed the problem of routing mechanisms 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 [1], under some conditions, the inefficiency of the LQI based routing. In this paper, we propose a simple way, to improve reliability and efficiency of the LQI based routing in WSN. We also evaluate other route selection criteria including the "remaining energy level" and the "sensor proximity with respect to the Base Station (BS)". The proposed local load balancing routing protocol is aimed to help source nodes to exploit potential capabilities of their respective neighbors without having any knowledge of their properties such as the position or the energy level. Simulation results show that our adaptation of the LQI metric is among the best route selection criteria regardless of the performance criterion under consideration, and that the load balancing significantly improves the routing efficiency by lengthening the network lifetime while minimizing packet losses.**

***Keywords*-Wireless Sensors Networks (WSN); Routing; LQI; Load Balancing; Remaining Energy; Degree of Connectivity; Round-Robin Routing; Weighted Round-Robin Routing; Wait and See (WaS) Protocol.**

I. INTRODUCTION

Designing a cold chain monitoring application requires special focus on at least two main phases. In [2], we present 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 [1], we used up to 50 Moteiv Tmote Sky [3] sensors, in a small experimental platform, including a 2.4GHz ZigBee [4] wireless transceiver (chipcon′s CC2420) [5]. On each packet reception, the CC2420 calculates the error rate, and produces a LQI value. To conduct experiments, we used the multiHopLQI routing algorithm along with the Sensornet Protocol (SP) implementation [6]. 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 results pointed out that the LQI based routing could have negative effects on the network performance [1]. 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. Several works address WSN routing, but only few papers are related to the 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 of the network. Our work addresses this challenge: improving the 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. 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. 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 rate are taken into consideration to evaluate the effectiveness of routing mechanisms.

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

Many experimental studies related to WSN [1],[7], [8],[9] and [10] have shown that high unreliability of wireless links must be explicitly taken into account when designing routing protocols. The performance objective of maximizing the network lifetime was considered in [11] and [12]. Several works are related to WSN and ad hoc networks load balancing routing schemes [13],[14],[15],[16],[17], and [18]. In [13], authors show that distributing the traffic generated by each sensor node through multiple paths instead of using a single path allows energy savings. Paper [14] defines a network optimization problem used for performing the load balancing in wireless networks with a single type of traffic. In [15], authors study wireless network routing algorithms that use only short paths, for minimizing the latency, and achieve the load balance. In [16], authors introduce a collision awareness in multipath routing; while [17] propose a multipath routing protocol to address the congestion control issue in WSN. In [18], 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. [19] presents a resource-aware and link quality based (RLQ) routing metric. Based on both energy efficiency and link quality statistics, the RLQ metric in [19] is intended to adapt to varying wireless channel conditions, while exploiting the heterogeneous capabilities. Some works are taken into account the round-robin cluster based routing [20],[21] and [22], where clusterheads are selected on a round-robin fashion. In [23] 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 the goal of this paper. To save energy, we exploit the broadcast nature of wireless links, and the fact that our weights are built upon the achtophorous nodes capabilities instead of the ones of the source node.

III. ROUTES SELECTION CRITERIA

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 (BS)

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:

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

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.

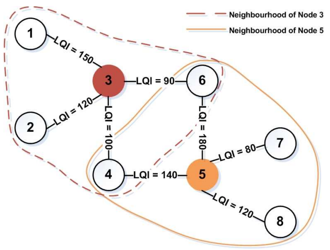

Figure 1. Example of a WSN with LQI values

Table I
LQI METRIC VALUES RELATED TO THE WSN IN FIG. 1

Sensor ID	1	2	3	4	5	6	7	8
AvgLQI	150	120	115	120	130	135	80	120
MaxLQI	150	120	150	140	180	180	80	120
MinLQI	150	120	100	100	120	180	80	120

D. Link Quality Indicator (LQI)

In Zigbee standard [4], 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 [4]. 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 [4].

For moteiv′s Tmote Sky [3] sensors equipped with chipcon′s CC2420 [5], the LQI values range from 50 to 110. Even so, we stick with the ZigBee standard [4] because some manufacturers, such as SUN-SPOT and WiEye, are still using the standard LQI values. Then, we use 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 [1],[6]. As for the MinLQI, it is the minimum value beyond the given LQI threshold. For example (Fig. 1), 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 80 (LQI of link 5-7). Thus, Table I gives LQI metrics values for the WSN in Fig. 1.

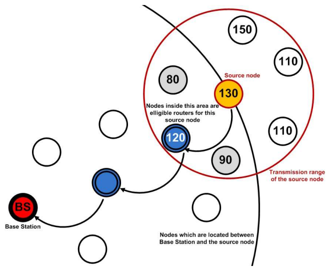

Figure 2. Simple routing

E. Composite Metric

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

$$Hybrid(LQI, M_i) = \alpha * LQI + (1 - \alpha) * Sc(M_i) \quad (2)$$

$$Hybrid(M_i, M_j) = \alpha * Sc(M_i) + (1 - \alpha) * Sc(M_j) \quad (3)$$

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):

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

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. $\beta = 50$, $\psi = 255$.

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

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 (Fig. 2).

B. Round-Robin Routing

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 (Fig. 3). This routing mechanism is a per-packet load balancing routing which gives most even distribution across next achtophorous nodes. This per-packet load balancing method means that

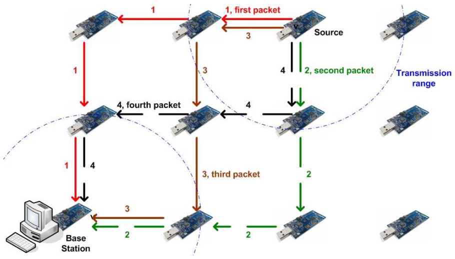

Figure 3. Round-robin routing

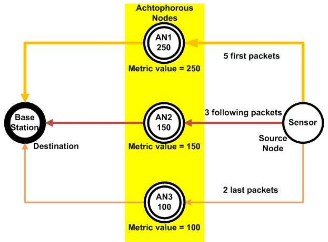

Figure 4. Weighted round-robin routing (W2R routing)

Table II
WEIGHT OF ACHTOPHOROUS NODES IN FIG. 4

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

packets in a particular connection or flow arrive at their destination out of sequence. This doesn't 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)*

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 (Fig. 4). 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 Fig. 4, 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.

V. LINK RELIABILITY BASED ROUTING PROTOCOL (L2RP)

The proposed (L2RP) routing protocol (Fig. 5) 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 phase:** 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 next hop is reliable or not. If the link is unreliable, based on the LQI value, it sends a "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 phase of the next cycle.

Upon receipt of a route request, a sensor S_i computes its own waiting time according to the following formula:

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

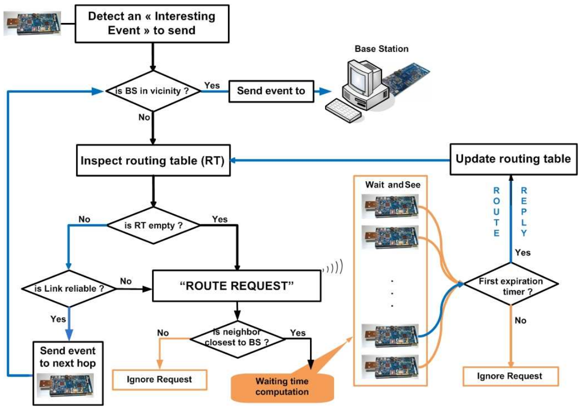

Figure 5. The Link Reliability based Routing Protocol (L2RP) flowchart

Where M_i is the metric value of the sensor S_i. τ and ζ are nonzero positive constants. Γ 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.

VI. PERFORMANCE CRITERIA

A. Average Rate of Remaining Energy

The average rate of 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. Load Imbalance Factor (LIF)

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:

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

Where E_R^i is the ratio of the remaining energy of sensor S_i; and $\overline{E_R}$ is the average rate of 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 the 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 [24],[25] 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

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. 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 $k_{data} = 128bits$, and the "ROUTE REQUEST" and "ROUTE REPLY" packets of the L2RP protocol have a size of $k_{rr} = 24bits$. Each node knows its position and its energy level. The initial energy amount of each node is set to $E_0 = (1.5 * 10^5 - \varepsilon)\mu J$, $\varepsilon = rand(0,1) * 10^2$. All nodes, including the BS, have same transmission range (R = 20m).

C. LQI Model for Simulation Purpose

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. Then, initial LQI values are calculated by using the $LQI(S_i,S_j)$ function defined below (similarly to the scale function Sc defined in the composite metric):

$$LQI(S_i,S_j) = \beta + \frac{\Psi * \log(1 + (\Upsilon_j^i - \Upsilon_{min}^i))}{\log(1 + \Upsilon_{max}^i)} \tag{9}$$

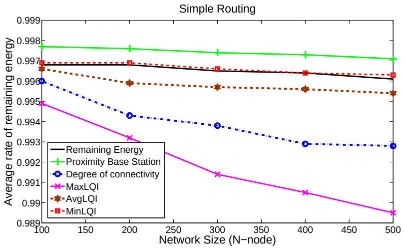

Figure 6. The average rate of the remaining energy (Simple Routing)

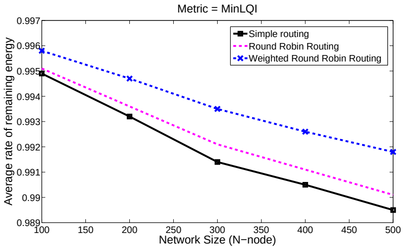

Figure 7. The average rate of the remaining energy (MaxLQI)

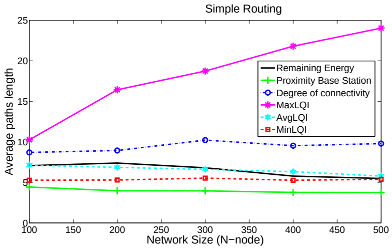

Figure 8. The average path length (Simple routing)

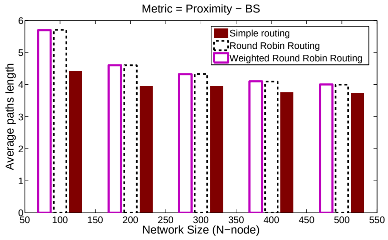

Figure 9. The average path length (Proximity Base Station)

Where $\beta = 50$, $\psi = 255$, $\Upsilon^i_j = 1/d(i,j)$, $\Upsilon^i_{min} = Min_j\{\Upsilon^i_j\}$, $\Upsilon^i_{max} = Max_j\{\Upsilon^i_j\}$ and $d(i,j)$ is the distance separating S_j from S_i. The choice of this model is guided by experimental results shown in [26] and [7] which stated that the LQI decreases when distance between nodes increases in Zigbee-based WSN. As we can see, $LQI(S_i, S_j) \neq LQI(S_j, S_i)$. Hence, our model allows to take into account asymetrical aspects of wireless links. This LQI model is only used for simulation purpose, 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, $\alpha = 0.5$ for the composite metric as defined in equations (2) and (3).

A. Average Rate of Remaining Energy

The Fig. 6 displays the average rate of the remaining energy after one short cycle in which sensors used the simple routing to elect their respective achtophorous node. The Fig. 7 displays the average rate of the remaining energy when MaxLQI is used as metric. It compares the simple and load balancing mechanisms.

The energy consumption is relatively low for "sensor proximity with respect to the BS", MinLQI, and remaining energy metrics. In contrast, degree of connectivity and MaxLQI metrics consume much more energy (Fig. 6). 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 chosen (the Fig. 7 shows the result for the MaxLQI metric). Load balancing routings are more energy efficient.

B. Average Path Length

The Fig. 8 shows the average path length for the simple routing; while the Fig. 9 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. For the MaxLQI metric (Fig. 9), the load balancing mechanisms have the same average path length, which is larger than the one of the simple routing. Likely, for all other metrics, load balancing routings have the effect of increasing the average path length and the weighted round-robin routing (W2R routing) produces the same average path length as the round-robin routing (Fig. 9). The two load balancing schemes, differ only on the way of distributing traffics (upon weights for W2R routing). Thus, for a source node, the same achotophorus nodes are to be selected for both W2R and round-robin routings. That is the reason why the average path length curves are identical in (Fig. 9) for the two load balancing mechanisms.

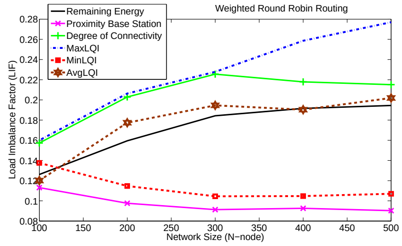

Figure 10. Load Imbalance Factor (W2R Routing)

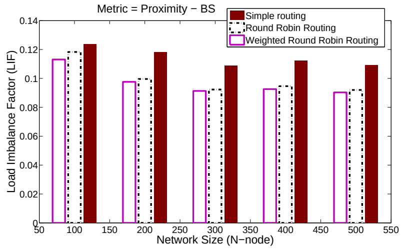

Figure 11. Load Imbalance Factor (Proximity Base Station)

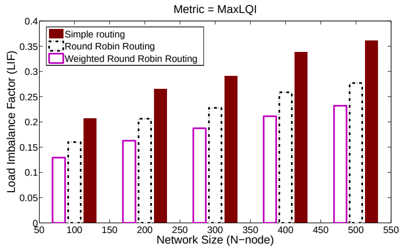

Figure 12. Load Imbalance Factor (MaxLQI)

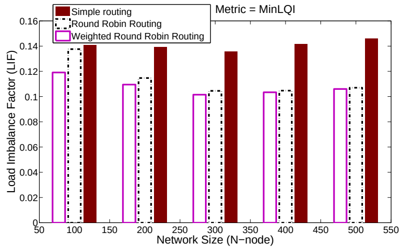

Figure 13. Load Imbalance Factor (MinLQI)

C. Load Imbalance Factor (LIF)

The Fig. 10 compares metrics in W2R routing. The Fig. 11 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 Fig. 12 for MaxLQI and the Fig. 13 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. The "Proximity with respect to the BS" and MinLQI metrics produce lower LIF values (Fig. 10). 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 (Fig. 10,12). This result confirms 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 (Fig. 11,12,13).

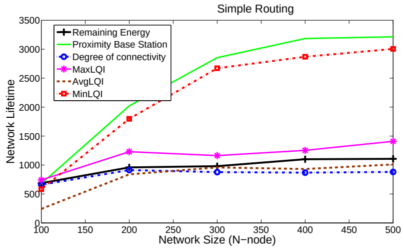

Figure 14. Average network lifetime (Simple Routing)

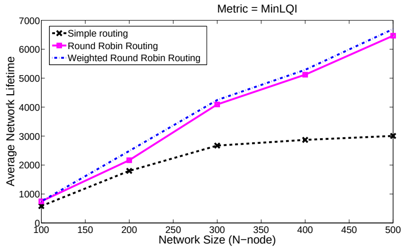

Figure 15. Average network lifetime (MinLQI)

D. Average Network Lifetime

The Fig. 14 displays the average network lifetime for the simple routing. The Fig. 15 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 (Fig. 14). Load balancing mechanisms significantly increase the network lifetime which is more large than the one of the simple routing with more differences for MinLQI (Fig. 15) and "Proximity with respect to the BS" metrics.

E. Average Percentage of Packet Losses

The Fig. 16 displays the average percentage of lost packets when the simple routing is run. The three routing mechanisms are compared (Fig. 17) using the degree of connectivity metric. Here again, best results are produced by MinLQI and "Proximity with respect to the BS" metrics. MaxLQI has an intermediate average rate of lost packets, while the

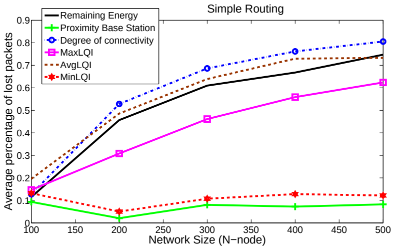

Figure 16. Average percentage of lost packets (Simple Routing)

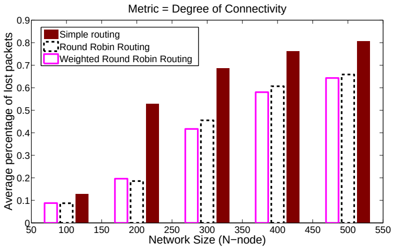

Figure 17. Average percentage of lost packets (Degree of connectivity)

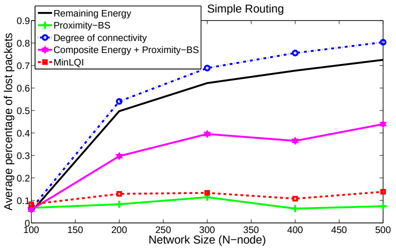

Figure 18. Average percentage of lost packets (Simple routing)

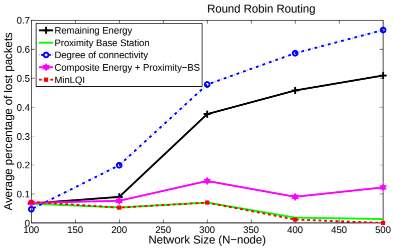

Figure 19. Average percentage of lost packets (round-robin routing)

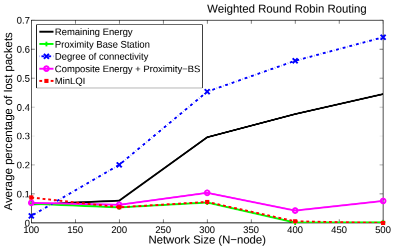

Figure 20. Average percentage of lost packets (W2R Routing)

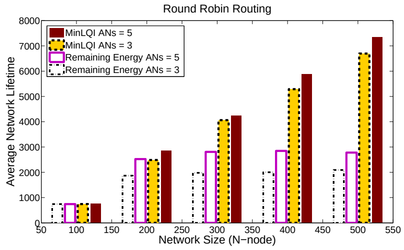

Figure 21. Average network lifetime (round-robin routing)

remaining energy and degree of connectivity metrics have higher rates. For all metrics, load balancing significantly reduces the average rate of packet losses (Fig. 17). 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.

F. Composite Metric (Hybrid)

The Fig. 18 (simple routing), the Fig. 19 (round-robin routing) and the Fig. 20 (W2R routing) display the average percentage of lost packets related to 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. $\alpha = 0.5$) is a very good metric. It has a rate of packet losses 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 (Fig. 18, Fig 19 and Fig. 20).

G. Impacts of Increasing the Number of Achtophorous Nodes

The Fig. 21 shows the influence of the number (ANs) of 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 Fig. 22 shows the influence of increasing the number (ANs) of 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 (Fig. 21 and Fig. 22) show that the average percentage of lost packets reduces 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.

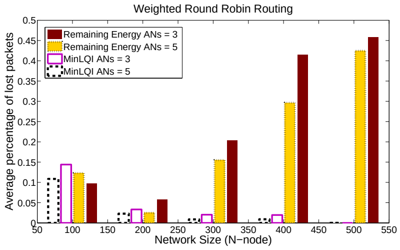

Figure 22. Average percentage of lost packets (W2R Routing)

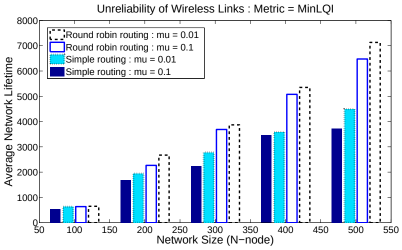

Figure 23. Unreliability of wireless links: Average network lifetime (MinLQI, $\mu = 0.01$ and $\mu = 0.1$)

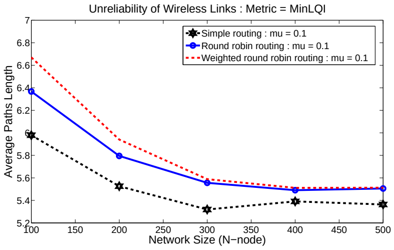

Figure 24. Unreliability of wireless links: average path length (MinLQI, $\mu = 0.1$)

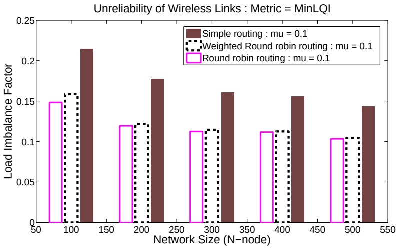

Figure 25. Unreliability of wireless links: LIF (MinLQI, $\mu = 0.1$)

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 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 Poisson process of parameter $\gamma(S_i)$ calculated as follows:

$$\gamma(S_i) = \frac{\mu}{\delta(S_i)} \tag{10}$$

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. For a sensor S_i, $\gamma(S_i)$ is too small, then the Poisson process returns integer series, in which nonzero values denote the unreliable links.

The Fig. 23 shows the effect of the unreliabilities of wireless links on the network 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 Fig. 24 (resp. the Fig. 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.

The first result in Fig. 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 too low unreliable environment ($\mu = 0.01$), even if the simple routing produces lower average path length (Fig. 24) than load balancing mechanisms. Even in the context of high unreliable links, the load balancing routing produces better LIF than the simple routing (Fig. 25), which means that the load is more evenly shared between nodes.

IX. CONCLUSION

In this paper, we evaluated the performance of a WSN routing protocol using load blancing mechanisms based on local route selection criteria (metrics) which include the link quality indicator (LQI). This work has shown that: 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 [1]. The MaxLQI metric matches the standard definition of the LQI used in the MultiHopLQI routing algorithm [6]. 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 metric which highly enhances the routing performance. As the LQI decreases when the distance between the nodes increases, the average path length is more large for MaxLQI than 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). The load balancing mechanisms significantly improve the routing efficiency by extending the network lifetime, while minimizing the average rate 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 "sensor proximity with respect to the Base Station" 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.

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