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Improving Network Lifetime with RPL through Energy Efficient Load Balancing

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Abstract—Efficient routing is needed in order to ensure a long lifetime of the Wireless Sensor Networks. Several routing metrics have been proposed to be used, however, energy efficient routing is still an open problem. In this paper, we propose a novel metric to prolong the lifetime of the network: the *Expected Lifetime* (ELT). ELT estimates the lifetime of a node by taking into account its residual energy, the link reliability to its neighbors and the quantity of traffic to forward. Therefore, we will be able to reduce the energy consumption, while keeping low packet losses and capturing the variations of the link quality. We apply this metric to RPL, the emerging routing protocol for low-power and lossy networks and show the lifetime gains of the network. Because we estimate ELT through passive measurements we provide here a detailed methodology to efficiently implement it with RPL.

Index Terms—WSN; RPL; routing metrics; energy balancing

I. INTRODUCTION

The lifetime of Wireless Sensor Networks (WSN) is very limited. MAC protocols that offer a low duty cycle (e.g. IEEE 802.15.4 [1]) became essential to extend the network lifetime, but not sufficient. Routing metrics and algorithms to minimize the energy consumption at the network layer have to be proposed.

RPL [2] is the new standard for routing in low-power and lossy networks, including WSN. For constructing the network topology, RPL can use several routing metrics [3]:

- node metrics: node characteristics, hop count to the sink and residual energy of the node.
- link metrics: throughput, latency, link reliability and link color (semantic constraint).

From all these metrics, the ones that can be used to improve the network lifetime is the residual energy and the link reliability, since it approximates the energy spent by a node for a successful reception.

If we use the residual energy of a node as a routing metric, the link quality is not taken into account. In this way, weak links can be chosen to relay the packets and the concerned nodes spend more energy for retransmission.

If we consider the link reliability (e.g. ETX [4]), a node may be able to estimate the energy budget for a successful reception at the destination. Thus, the routing protocol could avoid the nodes that are the most expensive in terms of energy spent per packet transmission. However, by using the minimum energy path to route all the packets, the nodes on that path will quickly run out of energy.

The problem of minimizing the energy consumption has been addressed outside RPL too. However, data dissemination

protocols or reactive protocols, do not account for the energy spent for the control packets in order to create and maintain the routes. On the other hand, most of the existing solutions for proactive protocols focus on considering the residual energy of the nodes while forgetting about link quality and hence, not taking into account the energy spent during retransmissions.

In this paper, we propose a new routing metric that estimates the *Expected Lifetime* of a node, according to the residual energy and the current traffic conditions. By appropriately constructing a network topology based on this metric, we are able to improve globally the network lifetime.

The contribution of this paper is threefold:

- 1) we propose the *Expected Lifetime* metric and show how to estimate it for each node;
- 2) we present an algorithm to compute a path metric, based on this node metric and taking into account the link quality, that will optimize the network lifetime;
- 3) we give a methodology on how to efficiently use ELT with a routing protocol that creates a tree or a directed acyclic graph topology (RPL in particular).

II. RELATED WORK

A. RPL: Routing Protocol for Low-power and Lossy Networks

RPL [2] is a distance vector protocol that constructs a Destination-Oriented Directed Acyclic Graph (DODAG) using one or more routing metrics. The DODAG construction is based on the *Rank* of a node, which depicts its relative distance to the DODAG root. An *Objective Function* defines how the metrics should be used to compute the *Rank*. In order to have a loop-free topology, the *Rank* must strictly monotonically increase from the root toward the leaves of the DODAG.

The construction and maintenance of the DODAG is ensured by DODAG Information Object (DIO) messages periodically broadcasted by all the nodes. When a node receives a DIO, it inserts the emitter in the list of possible successors (next hops to the border router). From all the successors in this list, the node will choose as preferred parent the one advertising the lowest *Rank*. It then computes its own *Rank* with the *Objective Function* and starts broadcasting itself DIO messages.

B. Energy aware routing

1) *Link quality based metrics*: De Couto *et al.* [4] have presented a pioneering piece of work to assess the link reliability in a radio environment and has been widely used

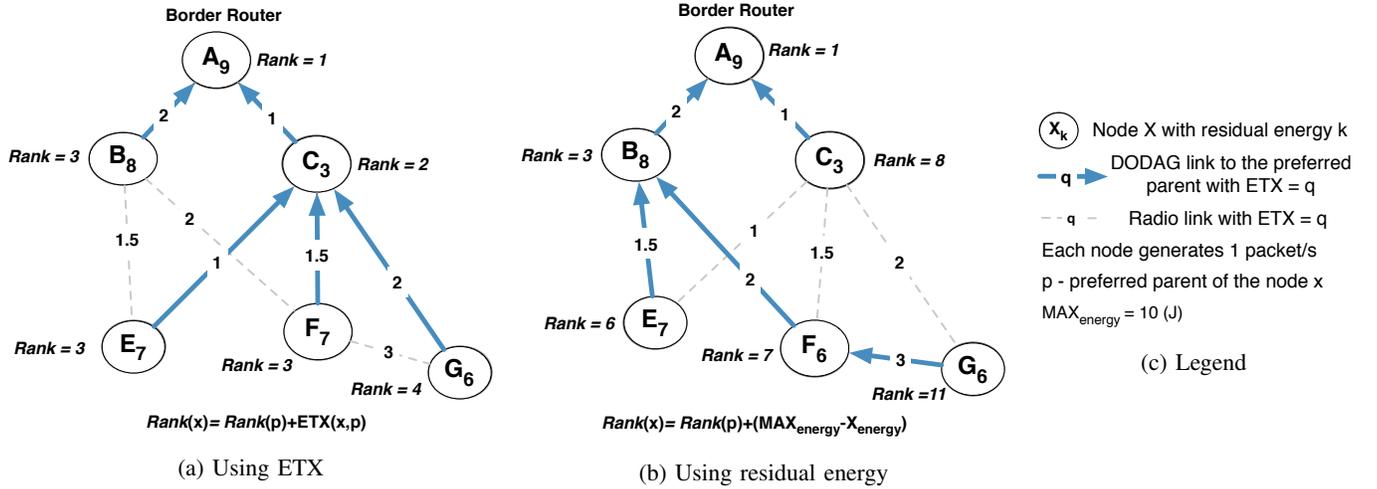


Fig. 1: DODAG construction using different routing metrics

with RPL [5]. The Expected Transmission count (ETX) estimates the number of required transmissions before a correct acknowledged reception. It is computed as:

$$ETX = \frac{1}{(PDR_{s \rightarrow d} \times PDR_{d \rightarrow s})} \quad (1)$$

where $PDR_{s \rightarrow d}$ is the estimated packet delivery ratio from s to d .

As a side effect, it also approximates the energy spent by a node for a successful reception, that is, the total energy consumed per unit flow or packet. However, this will result in a minimum energy path that will deplete the energy of the corresponding nodes, since all the packets will use this economic path. It will not improve the lifetime of the whole network and the resulted topology will not be energy balanced.

Lets consider the topology from Fig. 1a. E may choose either B or C as next hop. C is the most accurate choice, since it presents the lowest cumulative ETX towards the border router. However, if all the nodes generate the same amount of traffic, B should be preferred to balance the energy consumption.

2) *Residual energy based metrics*: A node should avoid having as next hop a node with a low residual energy, in order to improve the network lifetime. Dehghani *et al.* proposed to take into account the residual energy, the buffer size, the transmission delay and the packet reception rate [6]. In this way, they improve the load-balancing while reducing the delay. However, their proposal requires a huge periodical flooding. REER adopts a similar approach by using also the Signal-to-Noise Ratio (SNR) to discriminate bad radio links [7].

Yoo *et al.* use the residual energy depletion rate to avoid overloaded nodes [8]. The traffic load of a sensor is estimated as the energy dissipated in radio communication. Still, the path quality is not considered.

To the best of our knowledge, only Kamgueu *et al.* have proposed to use RPL with a residual energy metric [9].

However, they do not consider the radio link quality (and thus, the energy budget for a correct reception).

If we take a look at the topology depicted in Figure 1b we can observe that G can choose F or C as a next hop. Because the residual energy of F is greater, it will choose it as a parent, even though the corresponding link quality is very low (ETX=3).

3) *Other mechanisms*: In [10] the authors propose to maximize the network lifetime by taking into account the traffic generated and received by the nodes and the energy spent to send and receive data. However, unlike our proposed solution, they focus on finding the flow that maximizes the system lifetime and forget about MAC retransmissions. They formulate the problem using linear programming, but, they only present a centralized algorithm to route the packets, that performs close to optimal solution.

III. EXPECTED LIFETIME (ELT) - LINK METRIC

In this paper, we present a novel routing metric that will globally maximize the network lifetime. Through local decisions, but depending from each other (global objective) it manages to obtain an energy balanced topology.

A. Expected Lifetime Estimation

First, the routing metric should satisfy the following properties:

- capture the variations of the link quality (dynamic);
- maximize the reliability;
- minimize the energy consumption (e.g. retransmissions, overhead, etc.) of the whole network, and not just on a path. Balancing the energy should be preferred in order to prolong the network lifetime.

We propose here the metric *Expected Lifetime (ELT)*. A node will estimate its lifetime by taking into account:

- its residual energy;
- the link reliability to its preferred parent: the more retransmissions are needed, the more energy is consumed;

Notation	Meaning
$ELT(x)$	Expected lifetime of x
$E_{res}(x)$	Residual energy of x (in Joule)
$P_{Tx}(x)$	Energy spent per second when the radio is in transmission mode (in Watt or Joule/s)
$ETX(a,b)$	ETX of the link $a \rightarrow b$
$T_{total}(x)$	Throughput (bits/s) of x
$T_{gen}(x)$	Traffic generated by x
$C(x)$	Children set of node x
$P(x)$	Parents set of node x
b_x	Bottleneck of the path through node x
p_x	Preferred parent of the node x
$B(x)$	Bottlenecks set $B(x) = \{b_p p \in P(x)\}$
DATA_RATE	The rate at which the data is sent (bits/s); All nodes transmit at the same rate

TABLE I: Notation used in the article

- the quantity of traffic to forward: we take into account not only the traffic generated by a node, but also all the incoming traffic from its children.

The *Expected Lifetime* of a node may be computed as the ratio between its residual energy and the energy spent to transmit its traffic (i.e. the time before the node will run out of energy within the same conditions).

For the total traffic of a node x , we take into consideration the traffic generated by itself plus the one received from its children: $T_{total}(x) = T_{gen}(x) + \sum_{i \in C(x)} T_{total}(i)$. We consider that all the nodes transmit at the same rate: DATA_RATE. Moreover, the energy spent for the transmission of one packet takes into account the number of retransmissions at the MAC layer. Hence, this energy is computed as $ETX(x, p_x) \times P_{Tx}(x)$, where $ETX(x, p_x)$ is the average number of transmissions necessary for a packet to be successfully received by the node's preferred parent p_x and $P_{Tx}(x)$ is the energy spent to transmit one bit per second.

If $E_{res}(x)$ is the residual energy of node x , then:

$$ELT(x) = \frac{E_{res}(x)}{\frac{T_{total}(x)}{DATA_RATE} \times ETX(x, p_x) \times P_{Tx}(x)} \quad (2)$$

IV. EXPECTED LIFETIME - PATH METRIC

We now have to transform this node metric into a path metric. To be used with RPL, the associated *Rank* must be strictly and monotonically increasing.

Since we want to maximize the network lifetime, we need to focus our decision on the bottleneck in energy (i.e., the node that is more likely to be the first one to run out of energy). Thus, the weight of a path is the minimum ELT between all the traversed nodes. For example, in Fig. 2, the bottleneck of the path from G to A is the node C : it has the lowest ELT of the path.

A. ELT of a bottleneck: computation

Lets focus on the particular case when a node N wants to join the DODAG. Since the bottleneck is most likely to be the first node to die, the new node has to estimate the impact of

its own packets on the bottleneck's lifetime. But how does a node compute the ELT of a bottleneck?

To estimate the ELT of a bottleneck b , a node needs to know the following information:

- its residual energy: $E_{res}(b)$;
- the energy spent by the bottleneck to transmit one bit per second, taking retransmissions into account: $ETX(b, p_b) \times P_{Tx}(b)$ (the average number of retransmissions for a packet being given by the value of the ETX from the bottleneck to its parent);
- the total traffic handled by the bottleneck (packets generated by itself and packets received from its children): $T_{gen}(b) + \sum_{i \in C(b)} T_{total}(i)$;
- the rate at which the bottleneck transmits (DATA_RATE).

In order to save memory and energy, we need to compress this information, i.e., we should minimize the number of fields to insert in the DIO. If we take a look at the general equation, we observe that the terms of the equation can be separated into two variables:

$$ELT(b) = \frac{E_{res}(b)}{\frac{T_{gen}(b) + \sum_{i \in C(b)} T_{total}(i)}{DATA_RATE} \times ETX(b, p_b) \times P_{Tx}(b)} \quad (3)$$

The two variables will then be:

- avg_energy** spent by the bottleneck for a correct packet reception by the next hop:

$$\frac{E_{res}(b)}{ETX(b, p_b) \times P_{Tx}(b)} \quad (4)$$

- existing_traffic** forwarded by the bottleneck node:

$$\frac{T_{gen}(b) + \sum_{i \in C(b)} T_{total}(i)}{DATA_RATE} \quad (5)$$

where $T_{gen}(b)$ is the traffic generated by the bottleneck b , $T_{total}(i)$ the incoming traffic from the child i and C the set of children (cf. Table I).

Thus, besides the configuration parameters, a DIO will contain in its DAG Metric Container: the 2 variables: *avg_energy* and *existing_traffic*. Indeed, this information is sufficient for a new node N to accurately estimate the impact its traffic will have on the bottleneck b :

$$ELT(b) = \frac{avg_energy}{existing_traffic + \frac{T_{total}(N)}{DataRate}} \quad (6)$$

where $T_{total}(N)$ is the traffic injected by the new node on the path having the bottleneck b .

The ELT of a node (including of the bottleneck) is updated every time a DIO is being received. This way we can be sure that the information is kept up to date.

B. Preferred parent selection

When choosing its preferred parent, a node must consider both its own lifetime and the lifetime of the bottleneck, in order to estimate which of them becomes the new bottleneck.

We consequently propose the algorithm 1 for selecting the preferred parent (notation cf. Table I). For each possible parent (i.e., a neighbor advertising a *Rank* smaller than itself) a node x will:

- 1) compute its own lifetime when choosing this parent (line 2);
- 2) compute the updated lifetime of the bottleneck on that path with the new traffic injected by the node (line 3);
- 3) save the minimum lifetime among both (line 4).

Finally, the parent which presents the largest minimum lifetime is selected as preferred parent (line 6). The node then computes the new bottleneck of the path and updates the corresponding information in its DIOs.

Algorithm 1: Preferred parent selection

Data: $x, P(x), B(x)$

Result: preferred_parent of x

```

1 for  $p \in P(x)$  do
2    $elt_x = ELT(x)$ ;
3    $elt_b = ELT(b_p)$ ;
4    $Path_p(b_p) = \min\{elt_x, elt_b\}$ ;
5 end
6 preferred_parent =  $p$  such that
    $Path_p(b_p) = \max_{i \in P(x)} \{Path_i(b_p)\}$ 

```

C. Rank computation

The *Rank* of the nodes in the DODAG must be strictly monotonically decreasing towards the border router, in order to avoid the formation of loops. Since the *Expected Lifetime* represents a minimum metric along a path, its value cannot be used to compute the *Rank*: all the nodes in the sub-DODAG will have the same *Rank*.

We propose that a node computes its *Rank* by adding a constant step value to the *Rank* of its preferred parent:

$$Rank(x) = Rank(p_x) + Rank_increase \quad (7)$$

$$Rank_increase = Step \times MinHopRankIncrease$$

where *Step* is a scalar value and *MinHopRankIncrease* the RPL parameter [2]. This way, a node can have more options for choosing the preferred parent, while avoiding the formation of loops.

D. Illustration

If we take a look at the example in Fig. 2, G can choose as preferred parent the node D or F. If it chooses the path with the largest ELT for the bottleneck, it will become itself the new bottleneck, because the quality of the link between G and D is very bad (ETX=5), so it will need a lot of retransmissions for a packet to successfully arrive at D. Indeed, ELT of B will drop to 35, while G will become the new bottleneck with an ELT of 25. On the other hand, if G chooses F as a preferred parent, it will have a small impact on both the bottleneck (new ELT of C will be 30) and its own (ELT of G will drop to 45).

Finally, G will choose F, since it maximizes the minimum ELT between all the nodes in the network. G computes its

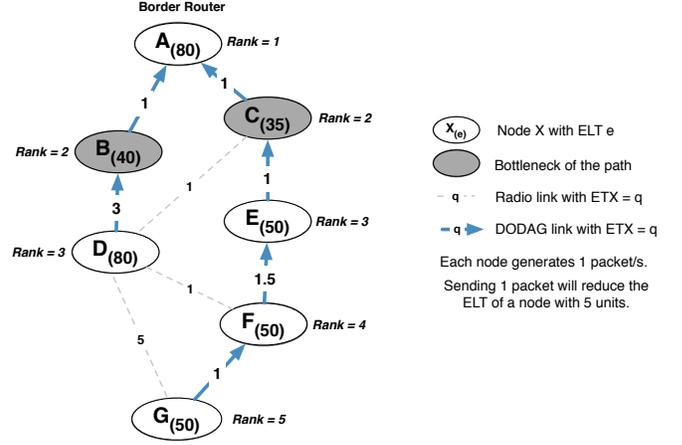


Fig. 2: Path selection with ELT (MinHopRankIncrease=1)

Rank as the *Rank* of its preferred parent plus a step value (in our case, 1) and starts advertising information about the new bottleneck of the path. The new bottleneck is the minimum value between its ELT and the ELT of the bottleneck of the path from its preferred parent to the sink (in this example, C remains the bottleneck of the path).

We can notice that in this example, the choice of the preferred parent would be the same in case ETX will be used as the routing metric. On the contrary, D will not choose the same parent if it uses ETX. It would choose C (ETX=1) rather than B (ETX=3).

E. Loop freeness and consistency

Using the ELT metric for routing is safe, i.e., it satisfies the requirements of consistency and loop freeness [11]. Sobrinho proved in [12] that the necessary and sufficient conditions that a routing metric must fulfil for these requirements to be met are isotonicity and monotonicity.

A routing metric can be represented as a quadruplet $(\Sigma, \oplus, w, \preceq)$, where Σ is the set of all paths, \oplus is the path concatenation operation, w is a function that maps a path to a weight and \preceq is an order relation. In our case, for a path p , its weight is the minimum ELT along the path ($w = \min(p)$) and the order relation is \geq : a path p is lighter than a path q if its expected lifetime is bigger.

1) *Isotonicity*: Let p and q be two paths in the network. The quadruplet $(\Sigma, \oplus, w, \preceq)$ is isotonic if $w(p) \preceq w(q)$ implies both $w(r \oplus p) \preceq w(r \oplus q)$ and $w(p \oplus r') \preceq w(q \oplus r')$, for all $p, q, r, r' \in \Sigma$. In other words, a metric is isotonic if the order relation between two paths is preserved if they are both prefixed or appended by a common third path.

We will prove the left isotonicity (in our case this means that if $\min(p) \geq \min(q)$ then $\min(r \oplus p) \geq \min(r \oplus q)$ for all $p, q, r \in \Sigma$). The right isotonicity (if $\min(p) \geq \min(q)$ then $\min(p \oplus r') \geq \min(q \oplus r')$) follows the same reasoning.

We can distinguish the following cases:

- $\min(r) \geq \min(p)$ & $\min(r) \geq \min(q) \Rightarrow \min(r \oplus p) = \min(p)$ and $\min(r \oplus q) = \min(q) \Rightarrow$

Parameter	Value
Simulation duration	3600 s
Number of nodes	50
Simulated area	300m x 300m
Traffic type, rate	CBR, 1 pkt/min
Data packet size	127 bytes (incl. MAC headers)
RPL	MinHopRankIncrease = 256
Trickle	$I_{min} = 2^7 ms$, $I_{max} = 16$, $k = 10$
MAC layer	802.15.4 mode beacon
MAC parameters	BO=7, SO =2

TABLE II: Simulation parameters

$$\min(r \oplus p) \geq \min(r \oplus q)$$

- $\min(p) \geq \min(r) \geq \min(q) \Rightarrow$
 $\min(r \oplus p) = \min(r)$ and $\min(r \oplus q) = \min(q) \Rightarrow$
 $\min(r \oplus p) \geq \min(r \oplus q)$
- $\min(q) \geq \min(r)$ & $\min(p) \geq \min(r) \Rightarrow$
 $\min(r \oplus p) = \min(r)$ and $\min(r \oplus q) = \min(r) \Rightarrow$
 $\min(r \oplus p) \geq \min(r \oplus q)$

So, we can conclude that ELT is an isotonic metric.

2) *Monotonicity*: Let p be a path in the network. The quadruplet $(\Sigma, \oplus, w, \preceq)$ is monotonic if $w(p) \preceq w(r \oplus p)$ and $w(p) \preceq w(p \oplus r')$ for all $p, r, r' \in \Sigma$. In other words, a metric is monotonic if its path cost will not become heavier when prefixed or appended by another path.

Like for the isotonicity, we will prove the left monotonicity ($\min(p) \geq \min(r \oplus p)$ for all $p, r \in \Sigma$). The right monotonicity ($\min(p) \geq \min(p \oplus r')$) follows the same reasoning.

- 1) $\min(p) \geq \min(r) \Rightarrow$
 $\min(r \oplus p) = \min(r) \Rightarrow \min(p) \geq \min(r \oplus p)$
- 2) $\min(r) \geq \min(p) \Rightarrow$
 $\min(r \oplus p) = \min(p)$

We can conclude that the ELT metric is monotonic.

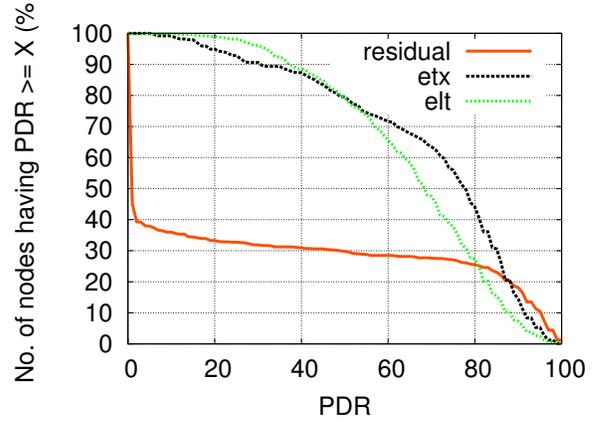
We have proved that ELT fulfils the isotonic and monotonic properties. Hence, the routing protocol will satisfy the requirements of consistency, optimality and loop-freeness.

V. SIMULATION RESULTS

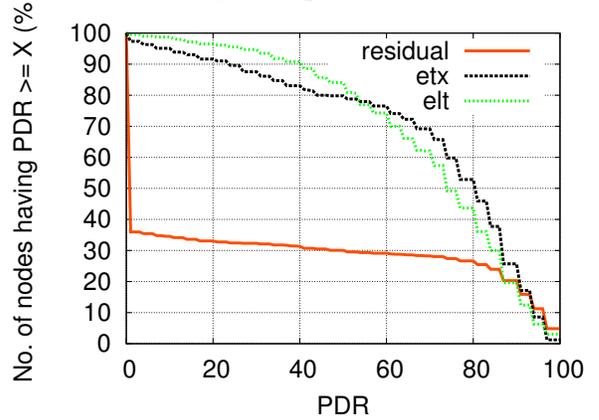
We adapted the RPL implementation of Contiki [13] to the WSN simulator, an efficient event-driven simulator dedicated to WSN, which has been extensively evaluated [14]. The results are averaged over 10 simulations with different random topologies. For the traffic, we considered usual CBR convergecast flows.

At the PHY layer, we used the path-loss shadowing model, calibrated with the scenario FB6 (indoor real deployment) presented in [15]: shadowing, path loss = 1.97, standard deviation = 2.0, $Pr(2m) = -61.4dBm$.

We configured RPL as illustrated in Table II. Both local and global repair are activated. In order to evaluate our solution, we compared the ELT metric with the other two metrics that take energy into account: residual energy and ETX.



(a) Considering all the period of the simulation



(b) After eliminating the first 30 min of the simulation

Fig. 3: ICDF of the end-to-end PDR

A. Reliability

We first evaluated the RPL reliability. Fig. 3a illustrates the inverse cumulative distribution function of the end-to-end packet delivery ratio. We can observe that ELT succeeds in having a PDR close to ETX.

If we take a look at Fig. 3b, where we eliminate the bootstrap period of the simulation (the first 30 minutes), we can notice that the gap between the two metrics becomes smaller. Moreover, ELT manages to have less packets with bad PDR than ETX. We have to keep in mind that ETX assumes that the MAC layer has an infinite number of retransmissions and so, a packet will arrive at the destination, independent of the quality of the link. In reality, this is not the case.

The residual energy has the worst end-to-end PDR, which does not come as a surprise: it tends to privilege nodes with energy, without taking link quality into account. This action results in bad links to be chosen to forward the packets.

B. End-to-end delay

We can see in Fig. 4 the inverse cumulative distribution function of the end-to-end delay of all the packets received by the border router. ELT has the largest delay among all the metrics: extra time is added because of retransmissions at the

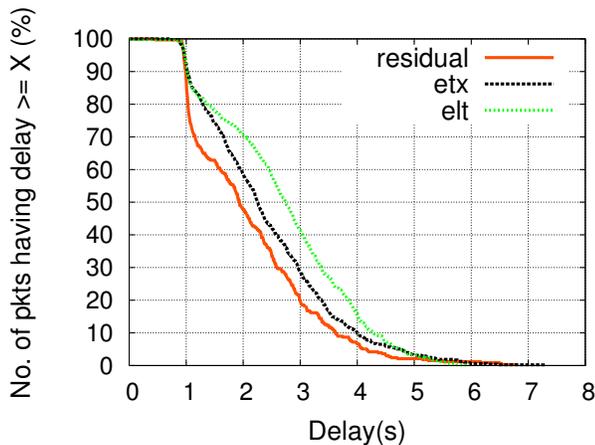


Fig. 4: ICDF of the end-to-end delay

MAC layer when nodes decide to choose a less good link for avoiding the overload of other nodes.

Still, ELT manages to have the best worst case with a maximum delay of 6 seconds (compared with the 7.4s of ETX and 7s for the residual energy).

The residual energy has the best delay because most of the packets are dropped, particularly by nodes far from the border router. Since the delay is computed only for received packets, nodes close to the sink (with shorter paths) are over-represented in the end-to-end delay result.

C. Energy consumption

Fig. 5 presents the box plot for the energy consumption of the nodes in function of their physical distance to the sink.

The residual energy has less energy consumption on average, but we have to not forget that its PDR is very low (60% of the nodes have PDR worse than when ETX and ELT is used). The less packets a node will transmit, the less energy it will consume.

ELT manages to have a better energy consumption than ETX, except for the nodes very close to the border router (at less than 50 m). Indeed, with ELT, these nodes will choose the border router as preferred parent, even if this means more retransmissions (and hence more energy consumption) in order to ease the traffic load of the other nodes.

We have to keep in mind that these results are of simulations that last for one hour. The gap between the difference in energy consumption will become larger with time and the gains obtained by using ELT should be even more important.

VI. CONCLUSION AND PERSPECTIVES

We highlighted that none of the routing metrics proposed to be used with RPL focuses on globally improving the network lifetime. We designed a new routing metric to prolong the network lifetime by energy balancing the load: the *Expected Lifetime*.

By using the ELT metric, the RPL protocol manages to have performance results close to ETX in terms of reliability and even surpassing it in the case of bad delivery. Indeed,

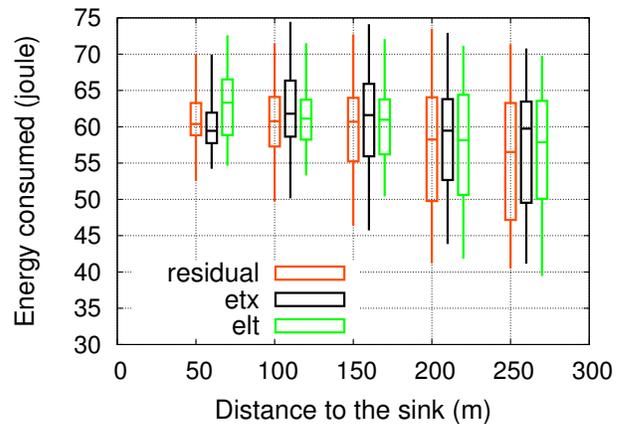


Fig. 5: Energy consumption in function of the node's physical distance from the sink

ELT manages to have less packets with bad PDR than ETX. Moreover, ELT manages to have the best worst case in terms of delay. All these, while having less energy consumption and a more energy balanced topology.

We plan to extend this metric to the multipath scenario. By optimally forwarding the traffic to several parents we could better distribute the energy consumption and hence, improve furthermore the network lifetime. However, we must take care of how many bottlenecks should a node advertise and how these bottlenecks are selected.

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