Comparison of RPL Routing Metrics on Grids

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Abstract. The IPv6 Routing Protocol for Low power and lossy networks (RPL) is appearing as an emerging IETF standard of Wireless Sensor Networks (WSNs). RPL constructs a Direct Acyclic Graph (DAG) according to an objective function that guides the routing based on some specified metric(s) and constraint(s). In the last decade, a number of RPL simulations have been proposed for several metrics and constraints, but for the best of our knowledge there is no comparative evaluation for RPL energy-aware routing metrics. In this paper, we present the first comparative study of RPL energy-aware routing metrics on Grid topology. Our experiments show that multi-criteria metrics perform better.

Keywords: RPL · Energy-aware routing metrics · Evaluation

1 Introduction

Wireless Sensor Networks (WSNs) remain an emerging technology that has a wide range of applications including environmental monitoring, smart space and robotic exploration. WSN are characterised by constrained nodes with limited processing capabilities and memory, which are typically battery-operated and interconnected by wireless links that are operating at a low data rate. WSN are usually experiencing a high loss rate coming from the low power and lossy nature of the links. Such constraints combined with a typical large number of sensors have posed many challenges related to the configuration, management and routing. In order to tackle this issue, the IETF has standardised RPL [WTB+12], a new IPv6 routing protocol especially taylored for Low power and Lossy Networks (LLN). In compliance with the IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) standard, RPL supports the idea of applying IPv6 [MKHC07] even to the smallest device by providing a mechanism whereby multipoints-to-point traffic from sensors inside the 6LoWPAN network towards a central control point (e.g., a server on the Internet) as well as point-to-multipoint traffic from the central control point to the sensors inside the 6LoPWAN are enabled. Support for point-to-point traffic is also available. For this purpose a Destination Oriented Directed Acyclic Graph (DODAG) is built. This DODAG is constructed using an objective function which defines how the routing metric is calculated. In particular, this objective function determines how routing constraints and metrics are taken into account to determine the best route. During the last decade,

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several metrics and constraints have been considered, e.g., ETX, ENG-TOT, ENG-MinMax (see Sect. 2.1 for more detailed).

In this paper, we compare the performance of several RPL routing metrics proposed for saving power and maximizing lifetimes. To the best of our knowledge, this is the first comparative study of RPL routing metrics. We conduct our experiments on top of the Cooja simulator [ODE+06], using Contiki OS 3.0. Simulation results show that multi-criteria metrics perform better.

The remainder of this paper is organized as follows. We first provide in Sect. 2 an overview of RPL and its related metrics. Then, we present an evaluation of the performance of energy-aware routing metrics (Sect. 3). We conclude this article with a summary of our contribution along future work.

2 Background

The Routing Protocol for Low power and lossy network (RPL) [WTB+12] has been proposed by the IETF Routing Over Low power and Lossy networks (ROLL) working group. RPL is a distance-vector routing protocol targeting IPv6 networks. In compliance with the IPv6 architecture, it builds a Directed Acyclic Graph (DAG) so as to establish bidirectional routes between sensors. RPL is mainly designed to exchange data between each (RPL) node and a particular node, called sink node. The sink node acts as a common transit point that bridges the LLN with the IPv6 networks. It also represents a final destination node. The traffic flows supported by RPL, include sensors-to-sink, sensor-to-sensor, sink-to-sensors. A sensor network can be used for different applications and several sink nodes can coexist, i.e., we can have potentially one sink per application. A Destination Oriented DAG (DODAG) is constructed for each application according to a specific function (called Objective Function) which optimizes a specified metric for data routing, e.g., minimizes the network distance. Every DODAG is rooted at the corresponding application sink (DODAG root). Some applications can optimize objective function, which may be contradictory with another application. To this end, the concept of RPL instance has been introduced. A RPL instance brings together a subset of DODAGs in a sensor network which follow the same objective function. Several RPL instances can run concurrently, but a node belongs to at most one DODAG per RPL instance.

RPL separates packet processing and forwarding from the routing optimisation functions which may include minimising energy, latency and generally speaking satisfying constraints. In particular, RPL provisions routes towards the DODAG roots which is optimised with respects to the Objective function. In order to create and maintain a DODAG, RPL specifies a set of ICMPv6 control messages, such as DODAG Information Object (DIO) and DODAG Information Solicitation (DIS). The root starts the construction of the DODAG by broadcasting a DIO message carrying several parameters, including an affiliation with a DODAG (DODAGID), a rank which represents the position of the node with regards to the DODAG root, a routing cost and its related metrics, a Mode of Operation (MOP). The nodes that are in communication range with the root decide whether to join the DODAG or not. In particular, based on the neighbours ranks and according to the objective function, each node selects its DODAG parent. For this purpose, the node provision a routing table, for the destinations specified by the DIO message, via parent(s). Then, the node originates its own DIO message. Rather than waiting for the DIO message, node may also broadcast a DIS message requesting information from the other RPL nodes. Overall this DODAG root permits to support sensors-to-root traffic, which is a dominant flow in many applications.

Sensor-to-sensor traffic flows up toward a root and then down to the final destination (unless the destination is on the upward route). For this purpose, RPL establishes downward routes using Destination Advertisement Object (DAO) messages. DAO message is an optional feature. RPL supports two modes of Downward traffic: Non-Storing (fully source routed) or Storing (fully stateful). In the Non-Storing case, the packet travels towards the root before traveling Down; the only device with a routing table is the root that acts as a router, hence source routing is used, i.e., the root indicates in the data packet the full route towards the destination. In the Storing case, sensors are configured as routers and maintain a routing table as well as a neighbour table that are used to look up routes to sensors. Thus, packet may be directed down towards the destination by a common ancestor of the source and the destination prior reaching a root.

In order to increase the network lifetime, RPL uses a dynamic dissemination algorithm, called Trickle. This algorithm adapts the rate at which DIO messages are sent by adjusting a timer. A DIO message is sent every $Imin$ ms during the DODAG construction, and when the DODAG construction has converged this interval is doubled at each time period until reaching a maximum interval corresponding to $Imax$ ms. When the DODAG reconfigurate due to e.g. the addition of new nodes or the detection of an inconsistency, RPL resets the timer to $Imin$. RPL also includes a mechanism to detect and suppress loops in the DODAG, based on the ranks in the DODAG. This loop-free property is obtained by insuring that the ranks increases in a strickly monotonically fashion, from the sink toward the leaf nodes. Therefore, every node compares the ranks of its neighbors to detect inconsistency, which is materialised by e.g., the reception of a downward data packet from a neighbor with a higher rank. When node detects a loop, it initiates a route poisoning (i.e., it broadcasts an infinite rank) so as to trigger a reconstruction of its sub-DODAG.

2.1 Objective Functions

An Objective Function (OF) specifies the objectives used to compute the (constrained) path and to select parents in DODAG. In practice, it defines the translation of metric(s) and constraint(s) into a value called Rank, which approximates the node distance from a DODAG root. Regardless of the particular OF used by a node, rank always increases so that loop-free paths are always formed. The definition of the OF is separated from the core RPL protocol. It allows RPL to meet different optimization criteria for a wide variety of applications.

For a detailed survey on the OF, the interested reader may refer to [GK12]. The ROLL working group has specified two types of OFs: Objective Function zero (OF0) and Minimum Rank Hysteresis Objective Function (MRHOF). OF0 is the default objective function that uses the hop count as routing metric. The MRHOF minimizes the routing metric and uses the hysteresis mechanism to reduce the churn coming from small metric changes for a better path stability.

RPL supports constraint-based routing. A constraint may be applied to link or node, and, if a link/node does not satisfy the given constraint, it is pruned from the candidate neighbors set, hence leading to a constrained shortest path. A metric is used in association with an OF for route optimization. The ROLL working group proposes two types of metrics: the node metric and link metric. The node metric represents the node state (e.g., node energy, node hops). The Link metric reflects the route quality, e.g. latency, throughput, Expected Transmission count (ETX). These metrics can be additive or multiplicative, they can also refer to a maximum or minimum property along a path in the DODAG.

In order to construct and update the DODAG, each non-root node has to select a *preferred* parent. This selection is performed by computing the path cost for each parent (neighbor with a lower Rank). The *path cost* is a numerical value which represents a property of the path toward the sink node. It is computed by summing up the selected node/link metric to the advertised path cost. The best cost returned by the OF using the specified metric for each candidate parent is used to select the preferred parent, i.e., the parent on the path with the best cost. The path cost is computed again either if the node/link metric is updated or if a new metric is advertised. When MRHOF is used, according to the hysteresis mechanism the current preferred parent is changed if the difference between the current and the new path cost is at least equal to a specified threshold.

After selecting its preferred parent P, a non-root node q computes its rank $R(q)$ as follows: $R(q) = R(P) + \texttt{rank\_increase}$, with $R(P)$ defining the Rank advertised by P and `rank_increase` the rank increment. Note that a DODAG root advertises a Rank equal to `rank_increase`. The Rank and the path cost computed by each node are disseminated in a DIO message.

2.2 Some Routing Metrics Proposed for RPL

Several routing metrics have been proposed in the litterature to increase the network lifetime, to maximize the reliability or to minimize the latency. In this paper, we focus on the energy-aware routing metrics because the energy is a key criterion of wireless sensor networks.

One of the classical and popular routing metric available in several RPL implementations is the Expected Transmission count (ETX). ETX estimates the number of transmissions that take place through a link before the reception of a correct acknowledgment. This value can be computed as: $ETX = \frac{1}{PDR_{s \to d} \times PDR_{d \to s}}$, with $PDR_{s \to d}$ defining the estimated packet delivery ratio from s to d. More particularly, this estimated packet delivery ratio is computed as the ratio between the number of transmitted packets and the number of acknowledged packets, including retransmission(s). Then, among the neighbours

N_i, using MRHOF a node i selects as preferred parent, the neighbour characterised by the minimum ETX, i.e., $\min_{j \in N_i} ETX_j$. The lower is ETX, the better is the link quality. The Rank $R(i)$ of node i with preferred parent P is given by: $R(i) = R(P)+$`rank_increase`. It is disseminated by node i using a DIO message. ETX seems to be a good candidate to reduce the end-to-end delay. Indeed, the lower is the retransmission number, the better is transmission time for a data packet toward the sink. In addition, since communication is the most energy consuming activity, ETX allows to reduce the energy consumed at each node. However, this does not permit to select a route composed of nodes with high battery level.

In order to design an energy-aware route selection, the *residual energy* $ResEng_i$ can be used as a RPL metric. The residual energy is computed as the difference between the maximum battery level $MaxEng_i$ and the energy consumed $EngCons_i$ by a node i, i.e., $ResEng_i = MaxEng_i - EngCons_i$. The energy consumed by a sensor is due to the computation and the radio communication (i.e., transmission and listening). Demicheli [Dem14] proposed the first RPL metric which considers the energy consumed by sensor nodes along a path. The Rank $R(i)$ of each node i is obtained by adding an increment (fixed to 16 by the author) to the Rank $R(P)$ of its preferred parent P, i.e., $R(i) = R(P)+$`rank_increase`. Each node i sends in DIO messages its Rank as well as the *energy consumed along the path* $PathEngCons(i)$ in the Metric Container field, with $PathEngCons(i)$ equals to the sum of $PathEngCons(P)$ sent by its preferred parent P and $EngCons_i$. The preferred parent is the parent with the lowest energy consumed along the path. The main drawback is that a path toward the sink may contain a node with a very low residual energy. To tackle this issue, Xu et al. [XL13] and Kamgueu et al. [KNDF13] consider the residual energy as a routing metric. Xu et al. [XL13] have proposed to use RPL with a residual energy metric: the Rank $R(i)$ of node i is equal to the Rank of the preferred parent $R(P)$ plus the residual energy $ResEng_i$ of i, i.e., $R(i) = R(P) + ResEng_i$. Each node selects as preferred parent the one with the highest Rank, and i sends a DIO message with its Rank and an idle Metric Container field. Kamgueu et al. [KNDF13] define the cost of a path PW_i of a node i toward the sink as the minimum among the residual energies along the path. Therefore, each node sends in DIO messages its rank and its path cost using the Metric Container field. Every node i computes the path cost that can be obtained for each parent (as the minimum between its residual energy and the path cost sent by the parent), and selects as preferred parent the one with the maximum computed path cost, i.e., $PW_i = \min(\max_{j \in N_i}\{PW_j\}, ResEng_i)$, where N_i refers to the neighbours of node i.

Some applications require data transmission with a low delay. Several routing metrics have been proposed to minimize the end-to-end delay with RPL [DPZ04, ABP+04, KB06]. Chang et al. [CLCL13] propose an energy-aware metric which considers the number of retransmissions. For this purpose, the residual energy is combined with the ETX. Each node i sends its Rank and its residual energy $ResEng_i$ using the Container Metric field in DIO messages. The preferred parent is selected among the parent j of i which gives the minimum of the weighted function: $\alpha\frac{ETX_j}{Max\_ETX} + (1-\alpha) \times (1 - \frac{ResEng_j}{MaxEng})$, where Max_ETX and $MaxEng$ are respectively the maximum ETX value of a link and the maximum battery level of a sensor node. The Rank of each node is computed as it is done by the ETX metric (and described above). Recently, Iova et al. [ITN14] have proposed another routing metric, called Expected LifeTime (ELT), to better optimize the network lifetime. This metric takes into account the link quality, the residual energy and the traffic. First of all, each node i computes its expected lifetime ELT_i following Eq. 1:

$$ELT_i = \frac{ResEng_i}{T_i \times \frac{ETX(i,P)}{Data\_Rate} \times PowTX_i}, \quad (1)$$

where T_i is the traffic of i (in bits/s), $ETX(i,P)$ is the ETX value of the link to the preferred parent P of i, $Data\_Rate$ is the rate at which data is sent (in bits/s) and $PowTX_i$ is the power consumed by a radio transmission made by i. For each path in the DODAG, the minimum expected lifetime is propagated along the path using the Metric Container field of DIO messages. Each node i selects as preferred parent the one which gives the maximum expected lifetime, i.e., $\max_{j \in N_i} ELT_j$. The Rank associated to a node i in the DODAG is computed as for ETX.

Table 1 presents a brief summary of the RPL metrics described in this section, it also gives the topology considered by the authors to evaluate their metrics.

Table 1. Summary of the presented RPL Metrics

Paper	Energy-aware	Metrics information		Topology
		Energy	Link quality	
[GL10]	No	-	Yes	Grid & Random
[Dem14]	Yes	Energy consumption	No	Grid & Random
[XL13]	Yes	Residual energy	No	Grid & Random
[KNDF13]	Yes	Residual energy	No	Grid & Random
[CLCL13]	Yes	Residual energy	Yes	Random
[ITN14]	Yes	Residual energy	Yes	Random

3 Metric Evaluation

3.1 Simulation Setup

In order to simulate and analyze the performance of RPL, we use the Cooja simulator [ODE+06], a flexible Java-based simulator which supports C program language as the software design language by using Java Native Interface. We simulate a Wireless LLN consisting of 56 nodes which are emulated as Tmote

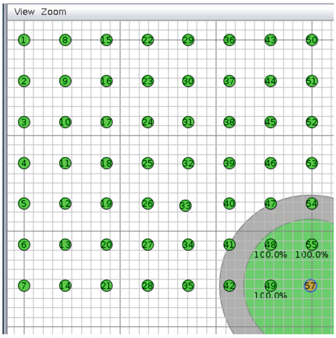

Fig. 1. Grid topology

Table 2. Node distribution on grid

Distance to the sink	Number of nodes
70 m	3
140 m	5
210 m	7
280 m	9
350 m	11
420 m	13
490 m	7

sky mote [PSC05] (a widely used sensor platform) with a 2.4 GHz CC2420 radio transceiver with IEEE 802.15.4 operating at the radio layer. These nodes are deployed over a 300×300 m grid with a sink located at the bottom right corner (Fig. 1). This sink location represents a worst case scenario (comparing to a sink located at the grid center): a higher congestion is observed around the sink because very few sensors are connected to the sink. The distance separating the nodes from the sink is given in Table 2. We use the ContikiOS 3.0 with ContikiMac [Dun11] which provides a power efficient medium access control by turning off the radio 99% of the time. We further rely on RPL as a routing protocol and we simulate a sensors-to-sink traffic wherein each node periodically sends to the sink some data packets, at a rate of 6 packets per minute, i.e., we consider Constant Bit Rate (CBR) convergecast flows. Note that each node starts sending its first data packet 65 s after the beginning of a simulation. The main parameters used for simulation are summarized in Table 3. TX rate and RX rate define respectively the success ratios in transmission and reception mode. We do not consider packet loss to better evaluate the performance of the metrics. We average the simulation results over 10 simulation runs, each one of 5 h duration.

3.2 Evaluation Criteria

In this study, we evaluate the influence of the metrics in terms of energy consumption, Packet Delivery Ratio (PDR), End-to-end delay and number of control messages exchanged.

– **Energy Consumption -** In order to compute the energy consumption, we rely on the Power-trace mechanism [DEFT11] provided by Contiki. The power-trace estimates the power consumption due to the CPU usage and the network-level activitities including packet transmission and reception. During our experiment, we focus on the period of time the radio is on. We further calculate the energy consumption $EngCons_i$ at each node i (in mJ):

$$EngCons_i = \frac{(T_{CPU} * I_{CPU} + T_{RX} * I_{RX} + T_{Tx} * I_{TX}) * Volt}{Rtimer} \qquad (2)$$

Table 3. Simulation parameters

Parametres	Value
OF	MRHOF
RPL MOP	NO_DOWNWARD_ROUTE
Start Delay	65 s
Imin	2^{12} ms
Imax	2^{20} ms
Data sent interval	6 pkt/min
RX and TX ratios	100%
TX Range	45 m
Interference Range	70 m

where $Volt$ corresponds to the battery voltage (=3 V), I_{CPU} (=1.8 mAh), I_{RX} (=20 mAh) and I_{TX} (=17.7 mAh) represent the current that has been consumed respectively during the CPU run time T_{CPU}, the radio listen run time T_{RX} and the radio transmit run time T_{Tx} (all expressed in ticks). *Rtimer* represents the number of ticks per second (=32768 ticks/s).

- **Packet Delivery Ratio (PDR)** is defined as the number of packets that are successfully received by the sink, divided by the number of packets sent by all the nodes to the sink.
- **End-to-end delay** is defined by the period of time between the packet generation by the node source in the application layer and its reception by the sink (in the application layer).
- **Control messages -** In order to reflect the cost and stability of RPL network topology, we trace the number of control messages (i.e., DIS and DIO messages) exchanged in the network.

3.3 Results

In the following, we present our results. In particular, we present the five following well known RPL metrics (that have been surveyed in Sect. 2.2) used to optimize the network lifetime:

- ETX: this is the default metric for RPL which considers the number of retransmissions for each link.
- Energy consumption: we consider the metric proposed by Demicheli [Dem14] in which the path cost represents the sum of the consumed energies, called *ENG-TOT* hereafter.
- Residual energy: we consider the metric proposed by Kamgueu et al. [KNDF13] wherein the path cost is given by the minimum residual energy on the path, called *ENG-MinMax* hereafter.

– Residual energy + ETX: we selected the metric proposed by Chang et al. [CLCL13] in which the path cost is equal to a weighted function integrating ETX and the residual energy, called *R* hereafter. The two parameters have the same weight in our simulation, i.e., we defined $\alpha = 0.5$.
– Expected lifetime: we choose the metric proposed by Iova et al. [ITN14] because it carefully models the network lifetime, called *ELT* hereafter. However, we do not implemented the expected traffic associated to each node, since it requires to exchange additional control messages to estimate the traffic in the sub-DODAG of each node.

The evaluation using the four criteria previously described for each of the above five metrics is presented in Fig. 2.

Energy consumption We consider first the energy consumed by each routing metric. In our simulation, all the nodes have the same characteristics and in particular have the same initial battery charge of 853 mAh. For a better use with the energy-aware routing metric, we have represented this charge in Cooja on a scale of 255 (as suggested in the RPL standard) and every step of 3.345 mAh decreases the battery level of one.

The percentage of time the radio is on reflects the energy consumed by the RPL protocol. In the first chart of Fig. 2, the energy consumption increases and then decreases as a function of the distance to the sink for the five metrics. This increase is due to the fact that the sink represents a bottleneck; packets are dropped which leads to a higher energy consumption. Then, as expected the energy consumption decreases as a function of the node distance. ETX is the routing metric which has the highest energy consumption, followed by the other energy-aware metrics ENG-MinMax and ELT, then ENG-TOT and R. The R metric achieves the lowest energy consumption, the radio is on at most 1% of the time.

Table 4 presents for each metric the percentage of energy consumed after 5 h of simulations and an extrapolation of the network lifetime expressed in days. It is noteworthy that the short network lifetime is related to the low initial battery charge (of 853 mAh instead of 2000 mAh in real Tmote sky mote platform [NF13]). We observe that the R metric outperforms all the metrics. It achieves a lifetime of 133 days, 5 to 7 times better than the other energy-aware metrics. Note that ENG-TOT has a good network lifetime after R metric, but it is a side effect of the low PDR reached (see below).

Packet Delivery Ratio. As shown in second chart of Fig. 2, the packet delivery ratio decreases as a function of the distance to the sink. ETX metric achieves good results with a PDR between 80 (for the farthest nodes) and 100% (around the sink), since it takes into account the link quality so as to choose the best parent. Comparatively, energy-aware metrics show poorer performance. The ENG-MinMax and ELT have a PDR between 25 (for the farthest nodes) and 95% (around the sink), while ENG-TOT metric has the worse PDR of 5% for the farthest nodes. The best results are given by the R metric with a PDR very close to

Table 4. Metrics lifetime

Time	Metric				
	ENG-MinMax	ENG-TOT	ETX	ELT	R
5 h	1.12%	0.38%	1.15%	0.97%	0.157%
	124698mj	42212mj	166098mj	107822mj	17359mj
Days	19	55	18	22	133

100% for any node. Better results are achieved by the R metric because it takes into account the link quality and the residual energy, contrary to ETX metric for which a certain amount of packets are lost due to the exhausted battery.

End-to-end delay. The third chart of Fig. 2 shows the results related to the end-to-end delay. The latency naturally increases along with the distance to the sink. ETX metric achieves better delays than energy-aware metrics since the link quality is not taken in account by the latter. As expected, we observe that reducing the number of retransmissions decreases the end-to-end delay. For the energy-aware metrics, ENG-TOT is close to ETX metric; ENG-MinMax metric gives the poorer results with a delay between 300 and 500 ms for most of the nodes except for the farthest nodes whose packets are transmitted with 900 ms delay. ELT metric is situated between ENG-TOT and ENG-MinMax metrics. The best end-to-end delays over all metrics are again obtained by the R metric with end-to-end delays smaller than 200 ms for the farthest nodes and 100 ms for the other nodes in the network. It is up to 5 times better than the worst delays achieved by ENG-MinMax metric.

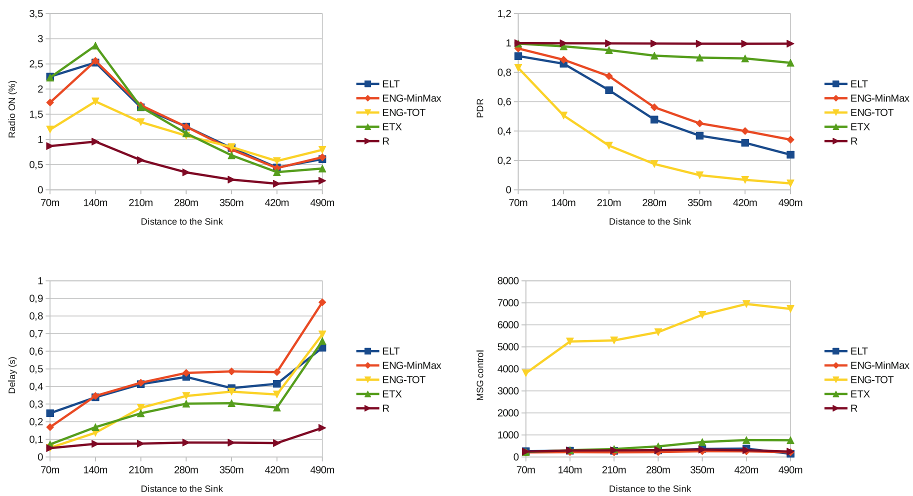

Fig. 2. Experimentation results for each implemented RPL metric.

Control messages. The overhead expressed as the amount of control messages sent by RPL increases slowly as a function of the distance to the sink. We observe a high overhead for ENG-TOT metric comparing to the other metrics; the overhead caused by ELT and ENG-MinMax metrics is relatively stable. The high amount of control messages for ENG-TOT metric is related to the low PDR achieved by this metric. In fact, the amount of control messages exchanged results from route instabilities in the DODAG. This has been analyzed by Boubekeur et al. [BBLM15] which address this problem by reducing the maximum number of children that a node can have. We note that, appart from ENG-TOT metric, the control traffic is negligible compared to the data traffic and as the DODAG stabilizes the control traffic decreases significantly.

4 Conclusion

To minimise energy consumption, guarantee a reliable communication and provide a high delivery ratio is especially challenging in WSN and necessitates to design special mechanisms at the network layer. As a result, RPL was specified by the IETF ROLL working group as a distance vector routing protocol for LLNs. A Destination Oriented Directed Acyclic Graph (DODAG) is constructed by optimizing an objective function which takes into account metrics and constraints for route selection towards the sink.

In this paper, we have presented the first comparative study of energy-aware metrics that have been proposed to enhance RPL and in particular extend the network lifetime. The default metric ETX considers the number of retransmissions and allows to reduce indirectly the end-to-end delay towards the sink. However, it reaches a poor network lifetime, despite it reduces the energy consumed for data transmission at each node. The widely used energy-aware RPL metrics achieve better network lifetime, but the end-to-end delays towards the sink may be important. Some energy-aware metrics, like ENG-TOT metric, have high end-to-end delays because of route instabilities in the DODAG. Moreover, it appears that bi-criteria metrics such as the R metric shows the best performance in terms of network lifetime and end-to-end delays. This can be explained by the fact that the parameters optimized by this metric are not orthogonal. Our results show that there is need for devising multi-criteria metrics that consider both the lossy nature of the link and the low power of the node to improve communication guarantee in WSNs.

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