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ORIGINAL RESEARCH

ETXRE: Energy and delay efficient routing metric for RPL protocol and wireless sensor networks

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Abstract

Internet of Things is an emerging paradigm based on interconnecting physical and virtual objects with each other and to the Internet. Most connected things fall into the category of constrained devices, with restricted resources (processing power, memory, and energy). These low-power and lossy networks (LLNs) are known for their instability, high loss rates and low data rates, which makes routing one of the most challenging problems in low-cost communications. A routing protocol for low-power and lossy networks (RPL) is a proactive dynamic routing protocol based on IPv6. This protocol defines an objective function (OF) that utilises a set of metrics to select the best possible path to the destination. Minimum rank hysteresis objective function (MRHOF) and objective function zero (OF0) are the most basic OFs, where the first one selects the path to the sink based on the expected transmission count (ETX) metric, and OF0 is based on the hop count (HC). These two metrics prioritise either brute performance (i.e. ETX) or simplicity (i.e. HC). Therefore, using a single metric with an OF can either limit the performance or have an inefficient impact on load management and energy consumption. To overcome these challenges, a routing metric based on MRHOF OF which takes into consideration the link-based routing metric (i.e. ETX) and node-based metric (i.e. remaining energy) for route selection is provided. Expected transmission count remaining energy (ETXRE) is evaluated through 36 scenarios with different parameters. Preliminary results show that ETXRE outperforms ETX and RE in terms of end-to-end delay by an average of at least 17%, packet delay by 13% and consumes 10% less energy.

KEYWORDS
delays, energy consumption, routing protocols, wireless sensor networks

1 | INTRODUCTION

The Internet of Things (IoT) is a new paradigm that emerged with the Fourth Industrial Revolution (i.e. Industry 4.0). This new concept revolutionises the way companies approach manufacturing and distribution processes. Industry 4.0 is based on the evolution of multiple technologies, such as IoT, artificial intelligence, analytics and machine learning (ML) [1]. IoT specifically connects physical things, such as vehicles, houses, sensors and virtual things (i.e. applications). The number of connected devices was 14.3 billion active IoT endpoints in 2022, and it is expected to reach 16.7 billion in 2023 [2]. This explosion is a result of the lower costs and ease of deployment. Furthermore, the IoT is more significant than ever. The COVID-19 situation shifted the narrative of automation and sensing from a luxury to a necessity. For example, contact tracking devices became mandatory in the health sector. The effort of the industry to maintain the production chain without human intervention gave the IoT even more ground and focus [3]. Wireless sensors are considered one of the pillars of IoT. Connecting these sensors with routers and gateways gave birth to a paradigm called wireless sensor network (WSN). The sensing nodes collect information from the environment and seek to reach the sink node. These devices are small, smart and resource-constrained. The most common usage of WSN nodes are agriculture, medical, military and security services.

WSNs can be categorised as low-power and lossy networks (LLNs) and feature communications with high data loss and low throughput. Traditional routing protocols are not suitable for LLN communications. To handle this set of use cases, the standardisation process covered the physical and medium access control layers through the IEEE 802.15.4 standard, adaptation layer with IPv6 for low-power wireless personal area networks (6LoWPAN), routing protocol for low-power and lossy networks (RPL) for network layer, and the constrained application protocol for application layer [4]. Despite these tiny devices' limited computing and battery capabilities, WSNs are anticipated to provide efficiency and reliability in transmitting and receiving sensing data in a strict and challenging environment. Therefore, WSNs should be able to overcome their resource-constrained nature and provide reliable data processing, packet transmission and energy efficiency. This need created an urge to design routing protocols tailored to these challenging requirements.

RPL was standardised as a result of cooperation between routing over low power and lossy networks (ROLL) and 6LoWPAN working groups. The design specifically targeted the IP-based communication between the resource-constrained IoT devices, the protocol is known for its robustness and efficiency. It also supports quality of service, flexibility and adaptability. Based on an objective function (OF), RPL proactively builds the paths after the initialisation of the network. The sensor node rank is used for the parent designation of each node. Two OFs were defined by Internet Engineering Task Force (IETF) and ROLL working groups: minimum rank hysteresis objective function (MRHOF) and objective function zero (OF0). MRHOF was designed with reliability and cost-efficiency considerations using a link-based metric such as the expected transmission count (ETX) or a node-based remaining energy (RE). OF0 only considers the number of hops to reach the sink [5]. Using a single metric for path selection has many issues. For instance, a single routing metric may be costly in terms of energy efficiency and load balancing. Some nodes will be selected more than others to form the destination oriented acyclic DAG (DODAG), which creates an unbalanced load distribution and can shorten the lifetime of the network.

The contributions of this paper include: (i) The proposal of the new routing metric called expected transmission count remaining energy (ETXRE) for MRHOF. This routing metric combines ETX and RE and inherits the performance of ETX while still providing efficient energy consumption (EC). (ii) The versatility and the wider range of the technical part as this paper evaluates 36 scenarios with three topologies (Random, Grid and Ellipse), number of nodes (30, 60, 90 and 120) and simulation times (convergence, 5 min and 10 min). (iii) The performance evaluation of ETXRE shows competitive results against ETX and RE in the convergence time, throughput and packet delivery ratio (PDR). ETXRE excels even more by outperforming ETX in the end-to-end delay (EED) by an average of at least 17%, packet delay by 13% and consumes 10% less energy. The remainder of this paper is organised as follows: Section 2 presents the related work. Section 3 introduces and motivates the usage of RPL protocol. Section 4 discusses the ETXRE routing metric. Section 5 breaks down the results of the simulation and compares the performance of ETXRE to that of ETX and RE. Finally, Section 6 concludes the study.

2 | RELATED WORKS

Routing protocol for low power and lossy networks (RPL) is a proactive routing protocol designed for constrained networks, and this protocol focuses on network formation and data exchange. RPL is one of the most widely used routing protocols in WSNs, thus much of the work concentrates on enhancing its overall performance and optimising the EC. In our previous work [6], we studied the RPL protocol, we also compared two of the most popular OFs MRHOF and OF0 based on several parameters, at the end of our work we concluded that MRHOF provides better overall performance, despite the simplicity of OF0, MRHOF optimises the path selection as the simulation time progress.

Paul et al. designed SIGMA-ETX [7], a new routing metric based on a combination of the minimum number of hops or the shortest path from OF0, and ETX from MRHOF. This new metric targets the problem of ETX bottlenecks. This process can be done by finding a balance between the number of hops and the ETX count. Despite the good performance of SIGMA-ETX in terms of network latency, PDR, lifetime and power consumption compared to that of the traditional ETX, the routing metric still struggles with dense networks with a much higher number of nodes. This solution is limited by the long hop problem and the inefficient load distribution. Compared to SIGMA-ETX, ETXRE takes into account the RE on the nodes, which is a critical aspect in WSNs. Many WSN use cases not only value the speed of the transmissions but also the efficient EC and the better battery lifetime for the sensitive nodes, that is, the ones physically located close to the sink node.

The hybrid objective function with empirical stability aware (HOFESA) [8] is composite OF based on a linear combination of three metrics: radio signal strength indicator, hop count (HC) and EC (or RE). HOFESA deploys several strategies from the DODAG information object (DIO) amendment to compute and select the parent, this includes adding the HC to the DIO messages (options field). The RE is computed locally by the nodes. The metric with the highest weight heavily impacts the selected parent. These three metrics are minimised to guarantee a loop-free path to the sink. This metric was compared with 25, 50 and 100 nodes, only the random topology was considered, and the simulation time was set to 5 min.

In the same context of composite objective functions. Hassani et al. [5] propose a new OF called IRH-OF. It is based on a single composite metric cmIRH, and this metric combines the benefits of signal indicator and HC. The tests show that this OF can maintain a PDR above 98% and reduces the average power consumption by 45%. Compared to this paper, our approach provides a more extensive and detailed simulation with different scenarios, leading to a deeper understanding of these hybrid routing metrics.

Gupta et al. [9] proposed a generalised MRHOF-based algorithm for parent node selection and deciding the most optimal path to the sink node. The simulation results show that a hybrid routing metric can be more suitable for small networks, whereas a single link-based metric is more preferred for larger networks. The authors suggest an analysis of the network's nature and make a reactive decision to choose the routing metric (single or combined) based on the desired application. Compared to this work, we evaluated ETXRE with multiple topologies, simulation periods and number of nodes. Our work can provide even more precise data on the performance of each routing metric.

Iova et al. [10] proposed a new metric to extend the lifetime of the network called the expected lifetime (ELT). This metric attempts to estimate the lifetime of a node based on several parameters, such as residual energy, link reliability and the amount of traffic to forward. This proposal has been evaluated through a WSN simulation, and the results show that the ELT can be interesting in terms of EC, but the ETX metric still provides better overall performance. Gaddour et al. [11] designed a novel OF called *OF-FL* by combining multiple parameters based on fuzzy logic. The authors compared OF-FL with MRHOF and OF0 and proved that OF-FL can provide better EC, EED and packet loss ratio than MRHOF with ETX and OF0.

Pasikhani et al. [12] took a different approach and focused on the reliability of the links. The proposed method link quality-based objective function (LQBOF) makes an approximation of the link quality using a link quality indicator (LQL). Compared to ETX, the authors see LQL as a better and more accurate link-based metric. LQL uses the PDR to rank the link from 1 to 7, then this value is integrated with the default ETX to find the best possible path. Compared to our work, LQBOF focuses more on the performance parameters. For instance, the PDR can be better than ETX only when the number of nodes is more than 100. Also, the latency is better only in the scenario of 50 nodes. ETXRE can provide a performance close to that of ETX, sometimes even better, and much-improved energy efficiency.

Telgote et al. [13] made a performance evaluation of four OFs OF0, MRHOF, MRHOF ETX and MRHOF energy. This work is consistent with our findings when it comes to the raw performance and the energy consumed by each of the OFs based on the placement of the sensor nodes and the number of nodes. However, this study lacks the scaling we are proposing in our work. The authors used only 30 nodes in their study with one topology and without any details about the performance per simulation time. We are also adding our new routing metric based on ETX and the RE to the compared routing metrics.

An alternative performance evaluation of RPL protocol done by Nazaralipoorsoomali et al. [14] with three routing metrics MRHOF ETX, MRHOF RE and OF0. This work shows a slight performance improvement based on the node placement. This is a logical result, as the closer the nodes are to the sink, they will use less energy to transmit and receive and also form the DODAGs. Compared to our work, the simulation only covers 55 nodes, where the nodes are randomly positioned. This is not usually the case as the sensor nodes are carefully placed to collect data from the environment, and it is needed to assess the impact of the topology used on the performance of the routing protocol. Moreover, our work covers more diverse simulation times instead of the 5-min scenario described in this paper.

VETX [15] is a routing metric based on the combination of ETX and the least number of hops (*HOPS*). The authors argue that *ETX* and *HOPS* are suitable solutions to select the best route in low-density network scenarios. But when the network grows, these methods tend to choose a longer path (more hops) to reach the destination. This problem can lead to bottlenecks and lower overall performance. VETX is believed to be more suitable for higher-density networks. This paper also combines two routing metrics to achieve better performance and an overall performance boost of 2.6% on average compared to MRHOF (ETX) and OF0. The drawback is more complex calculation which results in a higher EC. Compared to our work, ETXRE performs competitively with MRHOF (ETX) and surpasses it in the average delay, E2E delay and consumed energy.

Based on the recent survey in ref. [16], most of the existing works consider only random and grid topologies (about 88% of the considered papers). Knowing that WSNs are usually built and managed by an administrator, the placement of the nodes is intentional and some other topologies (e.g. Ellipse) can be more suitable for other use cases. Moreover, the considered studies mostly focus on PDR and EC and very few research papers (<10%) consider throughput or the network convergence time. These are also important parameters that can give a clearer idea of the network performance. Additionally, our routing metric ETXRE is based on both a node-based (RE) and a link-based metric (ETX) and simulates high-density scenarios (dozen nodes). Furthermore, our metric provides a consistently high PDR, lower EED, and consumes the least amount of energy, which leads to extending the lifetime of the network and unlocks a new set of use cases.

3 | RPL PROTOCOL: OVERVIEW AND MOTIVATION

3.1 | Routing protocols and WSN

Routing protocols can be defined as a set of defined rules used by the network devices to communicate between the source and the destination. In the context of WSNs, the sensor nodes need to transmit the sensed data to the sink node (or router). We can categorise the routing protocols into three categories: (i) Data collection protocols, this type tries to reach single or multiple destinations (e.g. sink node, base station etc.). (ii) protocols that provide peer-to-peer or any-to-any communications. (iii) protocols that allow one node to transmit to many other nodes to reach the destination.

The protocols of the first category create a routing tree where the sensor nodes select a preferred parent, and the messages are sent to the node's parent to the sink node. The second category allows the node to reach any other node in the network, this category requires a routing table prepared in advance. Finally, the last category has two types: flooding and gossiping. In flooding protocols, the sensor nodes broadcast the received messages to all the available neighbours except the source. This process will continue blindly until the packet reaches the destination or the HC reaches the defined maximum. Flooding techniques are simple, easy to implement and very basic. However, this simplicity also means unnecessary resource utilisation, less available bandwidth and more energy consumption. This can shorten the lifetime of a WSN. Gossiping protocols are a more intelligent version of flooding protocols, where sensor nodes transmit the data to a set of selected neighbours. This approach can solve some limitations of flooding protocols. But also increases the delay.

Data collection protocols can be either be reactive or proactive. Reactive (on-demand) protocols launch the route discovery only when there is a message to transmit. In this case, the route selection process is needed for every unknown destination, which can lead to a higher routing discovery time. Proactive (table-driven) protocol maintains a complete and recent list of routes to each destination. Therefore, even without any traffic, table-driven protocols keep an updated and consistent version of the table by sending the routing data to the other nodes. The example we will be examining in this paper is the RPL protocol, which falls into the proactive category.

3.2 | RPL protocol: Overview

Routing protocol for low power and lossy networks (RPL) is an IPv6 dynamic routing protocol designed by ROLL, a working group of the IETF that handles IoT routing topics. RPL protocol was specifically designed for devices with low processing power, low storage and limited batteries, thus constrained devices using low-power and low-cost communications. The protocol is table-driven and built upon a distance vector algorithm. RPL protocol creates a tree-like routing topology called Directed Acyclic Graph (DAG) divided into one or more DODAGs. The sink node can have only one DODAG which includes all the paths to the nodes on the tree [6]. RPL uses four ICMPv6 control messages for creating and maintaining the routing table and the DODAG:

- *DODAG Information Solicitation (DIS)*: If a single node wants to join a DODAG, and it did not hear any DIO message for a period of time, it sends a DIS message to know if there is any DODAG that can invite it.
- *DIO*: Used by RPL to create and maintain a DODAG. Once the RPL network starts, every node starts to send this message to its neighbours. DIO contains information about the node, whether it is storing or non-storing, and information about the DODAG configuration which can help the parents' designation process and invite the non-joined nodes to the DODAG.
- *Destination advertisement object (DAO)*: Used to propagate destination information upward along the DODAG.
- *DAO* can be used by a child to his parent as a request to allow him to join the DODAG.
- *DAO-ACK*: a response sent by a parent to a child meaning yes or no.

3.3 | Objective functions

An OF specifies the path selection process performed by RPL by using a list of metrics, the selected metric is shown in the RPL DIO metric container, and the routes are described using a value called 'Rank' calculated by RPL, the OF describes how to calculate the Rank value.

Links between sensors are not made equal and there are hardware constraints of LLNs with their limited storage and battery capacities. To fulfil those constraints, the choice of the OF can be critical. Two OFs have been defined, the OF0 [17] and MRHOF [18]. An OF is designed to find the best possible path by using the smallest path cost. Finding the least expensive path cost is based on two mechanisms: the first one tends to find the minimum path cost which is the path with the minimum rank, and the second one replaces the current minimum rank path with a new value if this new path costs less than the current minimum rank by a specified margin; this mechanism is called 'hysteresis'.

3.3.1 | Path cost calculation

A non-root sensor node with the ability to calculate the path cost needs to compute the path cost for each candidate neighbour. A neighbour path cost can be calculated by adding the selected metric (can be a link or a node metric) to the value of the metric container case in a DIO message (sent by a neighbour) [19]. ETX is the default metric used by the RPL.

3.3.2 | Parent designation

When the path cost calculation process is done, a node has to design a preferred parent to reach the sink node (upward routing). The candidate neighbour with the minimum path is selected as the current preferred parent, and the parent designation process is performed every time a new candidate neighbour joins the neighbour table or the path cost of a neighbour (including the current preferred parent) is updated.

3.3.3 | Rank calculation

The rank value calculation is heavily related to the parent path cost value, for example, if the chosen metric by MRHOF is ETX or Hopcount, the Rank value is equal to the path cost value of the preferred parent.

3.4 | Problem and motivation

MRHOF can be implemented with a single link-based metric such as ETX [6] or delay to the root, a node-based metric such as RE or a topology-based metric such as HopCount. The concern with single metrics can be noticed in terms of the performance of the DAG, for example, ETX suffers from high latency routing messages, which can be critical for real-time applications. The HopCount metric focuses on the shortest path without taking into consideration the remaining battery life of the nodes in this path, which can threaten the availability of the network with the failure of some of its components. Instead of using a single routing metric, we went for a composite metric based on ETX and RE, and this approach takes the advantage of the high performance of ETX and the load distribution features of RE to make an all-rounded routing metric with fewer trade-offs.

4 | ETXRE AND COMPARED PARAMETERS

4.1 | ETXRE: Combining ETX and RE

MRHOF runs ETX as a routing metric by default, and despite its elite performance ETX suffers from the intense EC caused by its complexity. On the other side in energy-aware routing, the path selection is based on the RE of the nodes, which can be more complicated than just finding the shortest path to the root based on the number of hops (HC). Despite the low overall EC of the HC routing metric, HopCount does not take into consideration the RE of a specific node and this can lead to an overload in certain paths and nodes, especially the non-powerful nodes located close to the sink that will have more packets to relay than other nodes which can lead to an energy depletion threatening the availability of the network. The path selection process by the RE metric can be expressed as shown in Equation (1).

$$\omega(\alpha) = RE^i = \frac{V^i initial}{V^i current}. \tag{1}$$

where, ω is the weight of the RE metric, i is the node in question, and V^imax and $V^i current$ are the RE of the node i on the initial state and the current state, respectively.

RE metric needs less power than ETX to operate, but it suffers from reliability problems. Both ETX and RE have their limits, and to overcome those limits we thought about combining the two into one routing metric.

Combining multiple primary routing metrics in one compound metric can optimise the performance of many parameters. But to avoid the loop-free problem, the monotonicity feature has to be valid. The additive routing metric can be defined as given below:

$$\begin{gathered}(\omega_1(\alpha), \omega_2(\alpha)) \prec_{add} (\omega_1(b), \omega_2(b)) \\ \Leftrightarrow \omega_1(\alpha) + \omega_2(\alpha) < \omega_1(b) + \omega_2(b)\end{gathered} \tag{2}$$

To make the compounded metric logical, the two main metrics used in the combination need to have the same order relation ($\prec$ or $\succ$), and the two combined metrics need to be monotones. Therefore, we have adopted this additive routing metric composition [20]. The weight of the path can be mathematically defined as shown in Equation (3).

$$\omega(\alpha) = a_1\omega_1(\alpha) + a_2\omega_2(\alpha). \tag{3}$$

where, ω is the weight of the metric in our case it is ETXRE, α is the link in question, and a_1 and a_2 are a pair of positive real numbers that represent the relative weights of the two metrics in question that is, ETX and RE.

To evaluate the performance of ETXRE which is the result of the composition of ETX and RE. We have chosen multiple parameters, and we took ETX and RE as a baseline. Next, we will describe each parameter used in this comparison.

4.2 | Compared parameters

MRHOF uses hysteresis while selecting the path with the smallest metric value and can use metrics such as ETX, RE, Hopcount etc. Next, we will describe each parameter compared in our simulation and the simulation details.

4.2.1 | Expected transmission count

ETX is the number of transmissions a node is expected to make to reach a destination successfully without error, MRHOF calculates the ETX of its neighbours and adds their value to the advertised rank to compute the associated rank of the routes. ETX is the default metric used by MRHOF, and is defined by the formula shown in Equation (4) [21]:

$$ETX = \frac{1}{(Df x Dr)} \tag{4}$$

where, Df is the probability of receiving a packet from the neighbour and Dr is the probability of receiving the acknowledgement (ACK) packet.

4.2.2 | Convergence time

The convergence time is the interval of time between the transmission of the first DIO message by the sink node and the instant in which all the nodes have joined the DODAG [22]. The convergence time ($Conv_{DODAG}$) parameter can be calculated as shown in Equation (5).

$$Conv_{DODAG} = \sum_{i=1}^{n} t_{join_i} \quad (5)$$

where, $Conv_{DODAG}$ is the convergence time of the DODAG and t_{join_i} is a variable representing the amount of time needed by a node i to join the DODAG. And n is the number of the DODAG nodes.

4.2.3 | Packet delivery ratio

The network performance can be measured through the ratio between the number of data packets successfully received by the destination and the number of packets transmitted by the source, and this ratio is known as the PDR, Mathematically, it can be defined as shown in Equation 6.

$$PDR = \frac{NP_{received}}{NP_{sent}} \quad (6)$$

where, $NP_{received}$ is the sum of data packets successfully received by each destination and NP_{sent} is the sum of data packets sent by each source.

4.2.4 | Throughput

This metric is defined by the total number of data packets successfully received over the simulation time. Mathematically, it can be defined as shown in Equation (7).

$$Throughput = \frac{P_{received}}{S_{time}} \quad (7)$$

where, $P_{received}$ is the sum of the bits successfully received by each destination and S_{time} is the total simulation time, a higher value of throughput means better connectivity.

4.2.5 | End-to-end delay

The average time needed for a packet to reach its destination is called the EED. The delay includes loss time caused by several reasons such as route discovery latency, queuing etc. Mathematically, it can be calculated as shown in Equation (8).

$$EED = \frac{Time_{required}}{NP_{received}} \quad (8)$$

where, $Time_{required}$ is the sum of time required for each packet to be successfully delivered, and $NP_{received}$ is the number of packets successfully received by all the sensor nodes.

4.2.6 | Power consumption

The power consumption is the amount of power needed by each node to run, and it contains four parameters: low power mode power, central processing unit power, radio listen power and radio transmit power. The summation of the four-parameter for all the DODAG nodes divided by the number of nodes represents the average power consumption ($Power_c$) by a node, as shown in Equation (9).

$$Power_c = \frac{\sum_{i=1}^{n} (LPM_P + CPU_P + RL_P + RT_P)_i}{n} \quad (9)$$

where, i is the concerned sensor node and n is the number of the DODAG nodes.

4.2.7 | Duty cycle

In order to optimise the power consumption, lower the heat generated by the sensor nodes, and to achieve a longer network lifetime, the radio unit must be switched off as much as possible. When the radio unit is unavailable, the sensor node cannot transmit or receive anything, and the challenge is turning the radio unit off in between the reception and transmission [23]. The Average duty cycle percentage ($Duty_{cycle}$) can be calculated as shown in Equation (10).

$$Duty_{cycle} = \sum_{i=1}^{n} \left(\frac{AT}{AT + ST} \right)_i \quad (10)$$

where, i is the concerned sensor node, n the number of the DODAG nodes, AT is the node's active time and ST is the node's sleeping time.

5 | PERFORMANCE EVALUATION

5.1 | RPL simulation details

To evaluate the performance of the RPL protocol, we have used the Cooja simulator in the Contiki Operating system. Cooja is a network simulator specialised in WSNs. We performed a total of 36 Scenarios with different network topologies, routing metrics and simulation times. The choice of the topologies was made to increase the credibility of the simulation and test our routing metric with different node positioning. Most of the current RPL-related papers only consider random and grid topologies [16], therefore we also added an Ellipse topology. Table 1 describes the technical details of our performed simulation.

To analyse the data collected from 36 simulation scenarios, we have created Table 2, and this table highlights the routing metric that performed the best for every single network topology and simulation time. The colours in the cells can be explained as:

TABLE 1 Simulation technical details.

OS	Contiki 2.7/Ubuntu 16.04
Simulator/tools	Cooja simulator/CollectView, JAVAScript editor, 6LoWPAN analyser
Parameters compared	*ETX*, *Hops*, $Conv_D$, $Power_c$, $Duty_{cycle}$, *PDR*, *EED*, *Throughput*
Topologies	Random, Ellipse and grid network
Routing metrics	ETX, RE and ETXRE
Nodes	30, 60, 90 and 120
Module type	SKY, SoC:MSP430, radio transceiver:CC2420
Radio medium	UDGM: Distance loss
Nodes range	50 m for TX and 100 m for INT
TX/RX ratios	100% for TX and RX
Applications	Sink (udp-sink.c) and senders (udp-sender.c)
Simulation time	CVT, 5 and 10 min

Abbreviations: CVT, convergence time; ETX, expected transmission count; ETXRE, expected transmission count remaining energy; INT, interference; OS, operating system; RE, remaining energy; RX, reception; TX, transmission; UDGM, unit disk graph medium.

- ETX: if ETX outperformed ETXRE and RE.
- ETXRE: if ETXRE outperformed ETX and RE.
- RE: if RE outperformed ETX and ETXRE.
- TieERE: if ETXRE and ETX are tied on top.
- TieERR: if ETXRE and RE are tied on top.
- TieER: if ETX and RE are tied on top.
- ALL: if all the three are equal.

We have also calculated the average values of the compared parameters including all three topologies and the four scenarios with 30, 60, 90 and 120 nodes (12 values). The following graphs (Figures 1–9) will give us a more accurate view of how ETXRE performs against ETX and RE.

5.2 | Results analysis

Now we can analyse all results recorded by our three routing metrics, starting with ETX.

5.2.1 | Expected transmission count

ETX routing metric dominates the ETX value. The metric comes first in 31 out of 36 scenarios and this includes all topologies, but ETXRE metric is not very far behind as shown in Figure 1, for example, the 10 min scenarios (12 scenarios) with ETXRE averaged 50.82 compared to 45.50 recorded by ETX metric (14% better), and, without surprises, RE came last with 96.26. We can also notice the average ETX in both routing metrics (ETX and ETXRE), that is, ETX is getting better as the simulation goes on while RE is slightly getting worse. This is because both ETX and RE are being optimised after the network convergence, unlike RE.

5.2.2 | Number of hops

ETX metric also has a slight edge regarding the number of hops to the sink because ETX metric focuses only on the maximum performance, and the number of hops is optimised without any consideration to the RE on the nodes. For 10-min scenarios, as shown in Figure 2, ETX averaged 3.45, ETXRE came very close with 3.54 (2.5% deficit) and RE finished last with 4.25. We can notice also that the number of hops did not change much as the simulation goes on for either of the three routing metrics. Regarding the performance difference based on the nodes' placement, ETXRE matches ETX in the random and Ellipse setting. But the grid clearly favours the ETX. This can be explained as the position of the sensor nodes in the grid is much more predictable, where ETX will easily select the best path compared to ETXRE who may select the more sustainable and longer path.

5.2.3 | Convergence time

ETXRE has a slight edge and beats ETX by coming first in 6 cases. ETX comes just behind with 5 and RE comes last with one win. On the other hand, we look into the average convergence time for the 120 nodes scenario (Figure 3). ETXRE records 253.62 s and has an edge of 2% over ETX who came second with an average of 258.24 s. And finally, RE with 688.35 s as an average convergence time. For the 90 nodes scenario, we can notice that the RE is looking like an outlier with a lower convergence time than the 60 nodes scenario. We ran the simulation multiple times in case it was an error on our part, but we still got similar results. After looking at the detailed recorded data, the random and the grid topologies were responsible for this unexpectedly low convergence time. The Ellipse topology result showed an increase from 225.18 to

TABLE 2 Routing metrics performance.

Network topology	Nodes & (S-time)	Compared parameters									
		ETX	*Hops*	*Conv$_D$*	*Power$_c$*	*Duty c_{Listen}*	*Duty c_{Trans}*	*PDR*	*EED*	*Packet delay*	*Throughput*
Random	120 (CVT)	ETX	ETXRE	ETX	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE
	90 (CVT)	ETX	ETX	ETX	RE	ETXRE	ETX	ETX	ETX	RE	RE
	60 (CVT)	ETX	ETX	ETXRE	RE	RE	RE	ETXRE	ETXRE	ETXRE	RE
	30 (CVT)	ETX	TieERE	RE	ETXRE	ETXRE	ETXRE	ALL	ETX	RE	RE
	120 (5 m)	ETX	ETXRE	X	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE
	90 (5 m)	ETX	ETX	X	ETXRE	ETXRE	ETXRE	ETX	ETX	ETX	ETX
	60 (5 m)	ETX	ETX	X	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE
	30 (5 m)	ETX	TieERE	X	ETXRE	ETXRE	ETXRE	TieERR	ETX	ETX	RE
	120 (10 m)	ETX	ETXRE	X	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE
	90 (10 m)	ETX	ETX	X	ETXRE	ETXRE	ETXRE	ETX	ETX	ETX	ETX
	60 (10 m)	ETX	ETX	X	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE
	30 (10 m)	ETX	TieERE	X	ETXRE	ETXRE	ETXRE	TieERR	ETX	ETX	RE
Ellipse	120 (CVT)	RE	TieERE	ETXRE	ETX	ETX	ETX	ETX	ETX	ETX	RE
	90 (CVT)	RE	TieERE	ETX	ETXRE	ETXRE	ETXRE	ETX	ETX	ETX	RE
	60 (CVT)	ETX	ETX	ETX	RE	RE	RE	RE	ETX	ETXRE	RE
	30 (CVT)	ETX	TieERE	ETXRE	RE	RE	RE	TieER	ETX	ETX	RE
	120 (5 m)	ETX	TieERE	X	ETXRE	ETXRE	ETXRE	ETX	ETXRE	ETXRE	ETX
	90 (5 m)	RE	TieERE	X	ETX	ETXRE	ETXRE	ETX	ETX	ETX	ETX
	60 (5 m)	ETX	ETX	X	RE	ETXRE	ETXRE	ETX	ETX	ETX	TieERR
	30 (5 m)	ETX	TieERE	X	ETX	ETX	ETX	RE	ETX	ETX	RE
	120 (10 m)	ETXRE	TieERE	X	ETXRE	ETXRE	ETX	ETX	ETXRE	ETXRE	ETX
	90 (10 m)	RE	TieERE	X	ETX	ETXRE	ETX	ETXRE	ETXRE	ETXRE	ETXRE
	60 (10 m)	ETX	ETX	X	ETX	ETX	ETX	ETX	ETX	ETX	RE
	30 (10 m)	ETX	TieERE	X	ETX	ETX	ETX	TieERR	ETX	ETX	RE
Grid	120 (CVT)	ETX	ETX	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	RE
	90 (CVT)	ETX	ETX	ETX	ETXRE	ETXRE	ETXRE	ETX	ETX	ETXRE	ETXRE
	60 (CVT)	ETX	ETX	ETXRE	RE	RE	RE	ETX	ETXRE	ETXRE	ETX
	30 (CVT)	ETX	TieERE	ETXRE	RE	RE	RE	TieERE	ETXRE	ETX	RE
	120 (5 m)	ETX	ETX	X	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE
	90 (5 m)	ETX	ETX	X	ETXRE	RE	ETXRE	ETX	ETX	ETX	ETX
	60 (5 m)	ETX	ETX	X	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE
	30 (5 m)	ETX	TieERE	X	ETXRE	ETXRE	ETXRE	TieER	ETXRE	ETXRE	ALL
	120 (10 m)	ETX	ETX	X	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE
	90 (10 m)	ETX	ETX	X	RE	RE	ETXRE	ETX	ETX	ETX	ETX
	60 (10 m)	ETX	ETX	X	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE	ETXRE
	30 (10 m)	ETX	TieERE	X	ETXRE	ETXRE	ETXRE	TieER	ETXRE	ETXRE	TieER

Abbreviations: CVT, convergence time; ETX, expected transmission count; ETXRE, expected transmission count remaining energy; RE, remaining energy.

298.49 s which is more realistic. In the 120 scenarios, the RE convergence time jumped to 1354.48 s in the random topology (×3.8 times compared to the 90-node scenario). This contributed to the higher average of the convergence time. In summary, the convergence time in RE is extremely unpredictable and highly volatile. This is because the preferred path

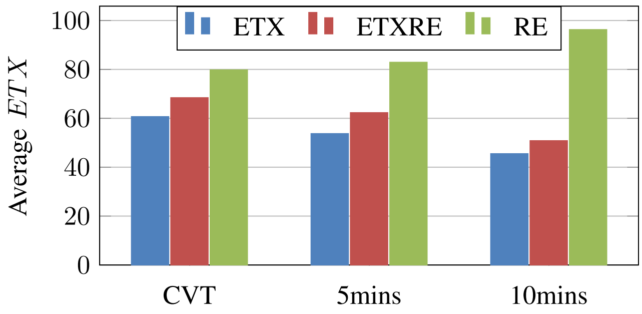

FIGURE 1 The average ETX value by the simulation time (lower is better). ETX, expected transmission count.

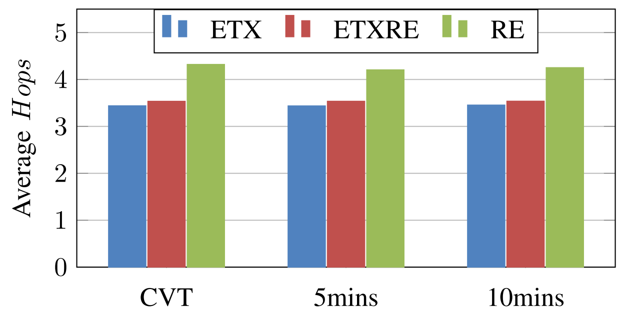

FIGURE 2 The average number of hops (hop count) by the simulation time (lower is better).

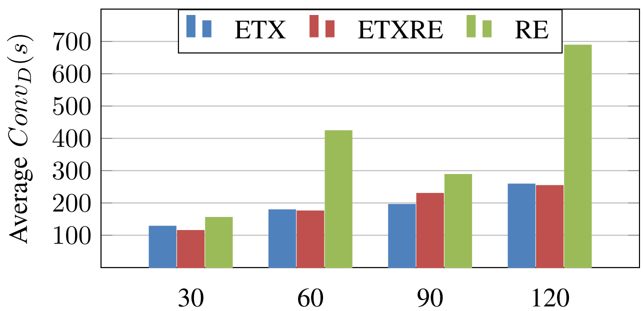

FIGURE 3 The average convergence time by the number of nodes (lower is better).

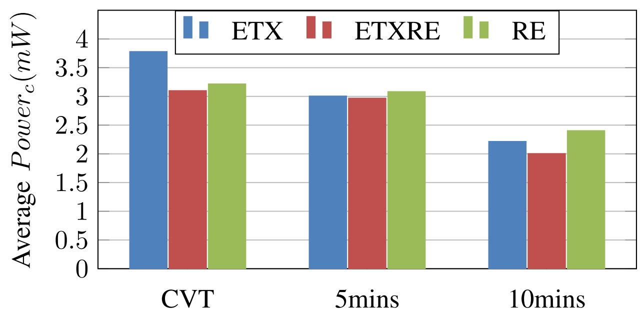

FIGURE 4 The average energy consumption by the simulation time (lower is better).

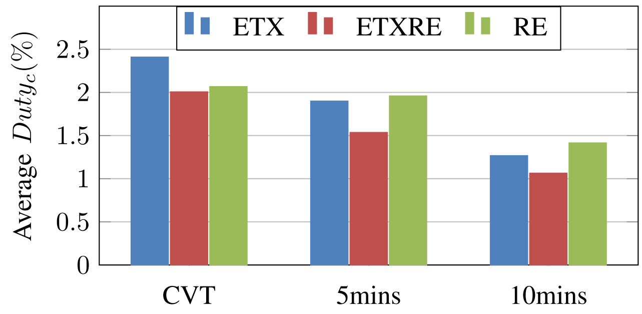

FIGURE 5 The average duty cycle percentage by the simulation time (lower is better).

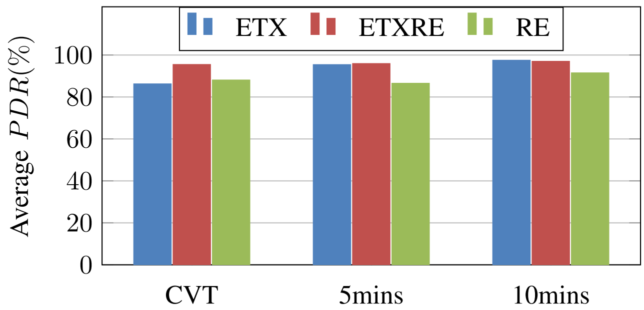

FIGURE 6 The average PDR percentage by the simulation time (higher is better). PDR, packet delivery ratio.

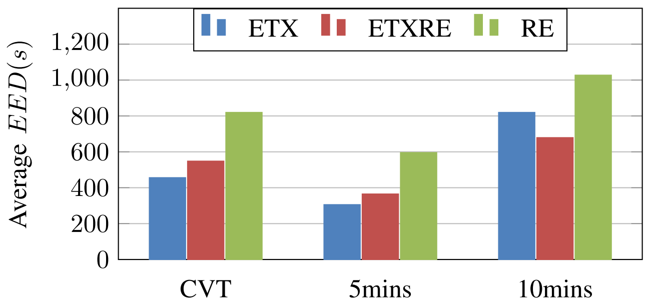

FIGURE 7 The average end-to-end delay by the simulation time (lower is better).

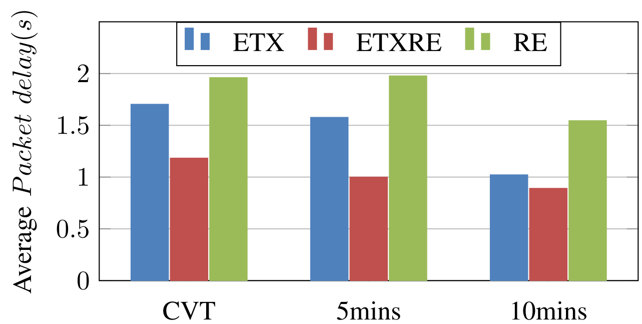

FIGURE 8 The average packet delay by the simulation time (lower is better).

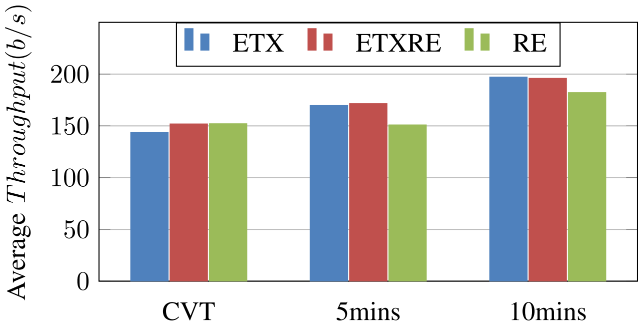

FIGURE 9 The average throughput by the simulation time (higher is better).

to the root is decided according to the RE on the sensor nodes. This means that the scalability of WSN based on RE needs more human intervention and sensor nodes placement is crucial for a better convergence time.

5.2.4 | Average power consumption

ETXRE consumes much less energy than ETX, which can be very interesting for low-power and low-cost networks. In almost all the scenarios, ETXRE was more efficient. If we take the average in the 12 scenarios of 10 min, ETXRE recorded 2.00 mW (mW), which is 10% better than ETX who finished with a mean of 2.21 mW, and 17% better than RE metric that averaged with 2.4 mW. Topology-wise, both random and grid topologies significantly favour ETXRE. Even in the Ellipse topology, the average EC within the 12 scenarios is 2.03 (mW) in ETXRE compared to 2.07 (mW) in ETX. The paired *t*-test in Figure 10 confirms the significance between two metrics in EC. This result can be explained with the intensive and more complex path calculation process by the ETX.

5.2.5 | Duty cycle

ETXRE dominates the EC parameters. For instance, it takes the top spot in both transmit and listen duty-cycle averaging 1.06%, which is 16% better than ETX which came second with a mean of 1.27%, and 25% better than RE which ended up with 1.42%. For the topologies, the duty-cycle follows the same pattern as the EC with the grid and the random, but for the Ellipse topology, it favours ETX in average with 0.92%, ETXRE is close with 0.90%, and finally RE with 0.79%.

5.2.6 | Packet delivery ratio

From Table 2, ETX and ETXRE are competitive in terms of the PDR (Figure 6). If we took the 10 min scenarios (where the RPL network is already established and optimised), ETX has a slight edge with 97.46%, ETXRE comes second with 96.95% and RE comes third with 91.45%. However, at the convergence time, ETXRE significantly beats both ETX and RE at the convergence time (95.44% in ETXRE compared to 86.2% in ETX and 88% in RE). ETXRE also has a slight edge in the 5-min scenario as ETX starts to catch up. This makes ETXRE an interesting option for applications that need a high PDR as soon as the network is built and initialised. ETXRE still provides a competitive PDR after the network is fully operational. If we compare the PDR within the context of the topologies, ETX and ETXRE look equal, even with the Ellipse that shows ETX winning most of the scenarios, it averages a PDR of 98.6%, ETXRE is a close second with 98%. Overall, the difference is within the margin of error according to *t*-test in Figure 10.

5.2.7 | End-to-end delay

The average EED of ETXRE and ETX is comparable (Table 2). However, when the simulation times are short (e.g. convergence time or 5 min), ETX provides a better average EED than ETXRE by 17%. Nevertheless, as the simulation goes on, ETXRE catches up to ETX and surpasses by 17% at the 10-min mark. At this point, ETXRE averaged 678.87 s, whereas ETX comes far behind with 819.46 s and finally RE with 1027.13 s. If we analyse the results from the topology lens, again the Ellipse is the topology where ETX dominates the most amount of scenarios as the EED averages 291.43 s compared to ETXRE 354.74 s, the rest of the scenarios favours ETXRE over ETX.

5.2.8 | Packet delay

When it comes to the packet delay, ETXRE takes the crown and records the lowest delay per packet in all three simulation times as shown in Figure 8. As time goes on, the recorded delay also gets better in all three routing metrics. In the end, in the 10-min scenario, ETXRE still performs 13% better than ETX and 42% better than RE. ETXRE needs an average of 0.89 s to send each packet to the sink node, ETX needs 1.02 s and finally RE requires 1.54 s. Based on Table 2, the packet delay follows the pattern of the EED, it favours ETX in the Ellipse topology over ETXRE (0.77–0.89 s). But the rest of the topologies and overall on average ETXRE still performs better.

5.2.9 | Throughput

From Table 2, RE gets the edge only at the convergence time, this means that RE performs the best in short working times, but when the network sets up after the convergence, ETX and ETXRE climb to the top once again. Now if we take the 10-min scenarios (Figure 9), ETX comes first with 197.05 bit/second, ETXRE comes just behind with 195.81 bit/s and RE with 182.01 bit/s. For the topologies, the throughput is competitive between all the routing metrics and surprisingly RE performs the best in the Ellipse topology. However, statistically, the difference is insignificant based on the *t*-test.

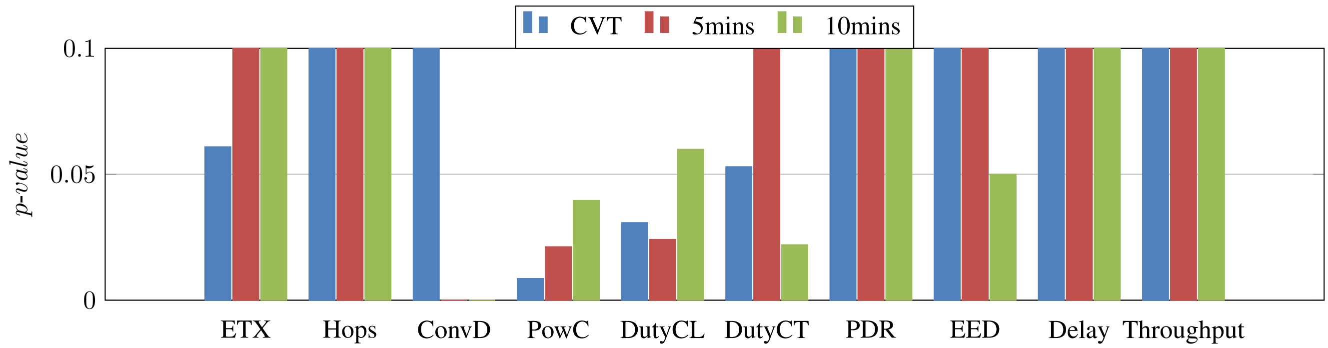

FIGURE 10 Paired t-test of ETXRE/ETX Routing metrics. ETX, expected transmission count; ETXRE, expected transmission count remaining energy.

To increase the confidence in these results, especially between the two most competitive routing metrics, a paired t-test was illustrated in Figure 10. The proposed pairs are the same and are used to calculate the averages at each simulation time and topology between the groups ETXRE and ETX. The probability p-value is shown in the graph, and it either suggests the statistical difference to be significant based on conventional criteria if the p-value is lower than 0.05 or not statistically different if it is more than 0.05. The results show no statistical difference in almost all the pure performance metrics between ETXRE and ETX except in the power consumption department. This suggests that ETXRE effectively consume much less energy. The duty cycle also mostly records a significant difference, especially in the listening part. This is largely due to long standby periods between active periods of the sensor nodes. Finally, the EED is showing a statistical difference only at the 10 min. This graph's overall deviation between the performance of ETXRE and ETX is mostly insignificant. Except in energy efficiency.

To select the best possible routing metric for MRHOF, we gave each metric a maximum score of 40 (30 for performance and 10 for the EC). The performance is represented by six parameters (***ETX***, ***Hops***, $\boldsymbol{Conv_D}$, *PDR*, *Delay*, *Throughput*), and the EC is represented by ($Power_c$ and $Duty_{cycle}$), a total of eight parameter each one weight five points.

- If a routing metric comes first, it will score 5 points for that specific parameter.
- If a routing metric comes second it will gain three points.
- One point if a metric comes last.

Table 3 highlights the final results.

ETX performs the best compared to ETXRE and RE, but it is close to ETX and ETXRE. In terms of EC, ETXRE presents by far the best management of the energy consumed by the RPL nodes. Finally, the node-based metric RE comes last in both categories. If we focus on the network topologies, from Table 2, in both grid and random topologies, ETXRE is the most optimal routing metric and provides a well-balanced performance in terms of the PDR and delay and is much more efficient in EC. For the Ellipse topology, ETX is overall better, and even RE gives a better throughput.

TABLE 3 Final score of each routing metric.

	Scores		
Routing metric	**Performance**	**Energy consumption**	**Total (/40)**
ETXRE	21.219/30	8.250/10	29.469
ETX	23.750/30	5.056/10	28.806
RE	11.094/30	4.722/10	15.816

Abbreviations: ETX, expected transmission count; ETXRE, expected transmission count remaining energy; RE, remaining energy.

Except in the Ellipse topology, where ETX is slightly ahead. ETXRE achieves a better and more consistent PDR even during the convergence time, it also consumes less energy and records lower delay to reach the sink in most of the simulated scenarios. All these advantages make ETXRE suitable for the new emerging IoT use cases such as healthcare. For instance, wearable devices are becoming a very popular choice for athletes to monitor their performance. The sensors are used to submit a report periodically to a centralised entity (Sink node), and the data are analysed in real-time to adjust the training process. In such a use case, a high PDR is required to minimise any data losses, also the packet delay should be optimised to make close to real-time adjustments or for future usage. EC may not be the most needed feature, but in the case of passive and continuous monitoring, ETXRE may be a more interesting option.

6 | CONCLUSION

MRHOF utilises a routing metric to find the best possible path. This calculated route will be used for all future transmissions of sensor nodes affiliated with the WSN. In this paper, we focused on two routing metrics, a link-based routing metric called ETX and a node-based one named RE. The combination of these two routing metrics has shown great potential to overcome the excessive EC of ETX and the performance limitations of RE in different topologies and scenarios. After analysing the 36 scenarios we proposed, RE performs the best in short durations (at convergence) but after the network stabilises, ETX and ETXRE catch up and surpass RE in all the metrics considered in this study. While ETX slightly outperforms ETXRE and beats RE by a considerable margin on average in pure performance, ETXRE outperforms ETX and RE in the delay and EC metrics. These results can be explained by a difference in the way the best possible route is chosen. RE focuses on balancing the load and extending the lifetime of the network, while ETX only cares about the fastest path. ETXRE takes the best of both worlds. The efficiency offered by ETXRE can be beneficial for multiple use cases that do not need the absolute fastest path to the sink node, and profit from the low EC, which can lead to longer network operating lifetime and less maintenance.

In our future work, we will explore ways to ETXRE and make it more dynamic and responsive through ML. With the amount of data collected, training a model to choose the best possible path for a specific use case and based on the current parameters (network load, sensors battery, transmission power etc.) can potentially have a significant performance and energy efficiency uplift.

AUTHOR CONTRIBUTIONS

Aiman Nait Abbou: Conceptualization; data curation; formal analysis; investigation; methodology; validation; writing – original draft; writing – review & editing. **Jukka Manner**: Project administration; resources; supervision; writing – review & editing.

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CONFLICT OF INTEREST STATEMENT

Dr. Aiman Nait Abbou has nothing to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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