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OF-EC: A Novel Energy Consumption Aware Objective Function for RPL based on Fuzzy Logic

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Abstract. Low-Power and Lossy Networks (LLNs) have recently emerged as a promising and attractive paradigm. The IPv6 Routing Protocol for Low Power and Lossy Networks (RPL), proposed by the IETF ROLL working group, is specifically designed for LLN and is compliant with the 6LoWPAN protocol. RPL has gained a significant maturity, and is still attracting more researchers contributing to its improvement. RPL builds a Destination Oriented Directed Acyclic Graph (DODAG) based on a set of metrics and constraints through specific Objective Functions (OFs). The OFs select the best parent of nodes to build and optimize the route. However, the standard objective functions have some limitations due to the use of a single metric. In this paper, we propose a new OF based on combined metrics using Fuzzy Logic (OF-EC). To overcome the limitations of the use of a single metric, the proposed OF-EC considers both the link and the node metrics, namely the Expected Transmission Count (ETX), Hop Count (HC) and the Energy Consumption (EC). The simulation results demonstrate the effectiveness of the new OF-EC in comparison with the MRHOF, ENTOT, and OF-FUZZY in improving RPL performances in terms of PDR, network lifetime, convergence time, latency, overhead, and energy consumption. Our results show that OF-EC keeps the RPL overall efficiency independent from the network topology and the transmission range. Moreover, the proposed OF-EC outperforms the other proposals in balancing the energy consumption of all nodes in the network**.**

Keywords—RPL; MRHOF; OF0; Fuzzy Logic; Energy consumption.

I. Introduction

The concept of connecting an everyday object to the Internet remains the primary objective of the Internet of things (IoT) (Lin et al., 2017) (Lamaazi, Benamar, Jara, Ladid, & Ouadghiri, 2013) (Atzori, Iera, Atzori, Iera, & Morabito, 2010). It supports data sharing over a global network (Ashraf & Habaebi, 2015) infrastructure of interconnected smart objects for different domains as healthcare, military, environment and industrial monitoring (Pease, Conway, & West, 2017). The big challenge of IoT is to find solutions for applications used in a constrained environment, especially those implemented on tiny devices (Diaz, Martin, & Rubio, 2016). These devices are battery powered and have short transmission range, small battery lifetime and low communication bandwidth (Lamaazi, Benamar, Jara, Ladid, & Ouadghiri, 2014) (Kong, Ang, & Seng, 2015). They aggregate their capabilities through inter-device coordination and data sharing. The resource constraints and the noisy environment arrangement results in a Low Power and a Lossy Network (LLN) that needs particular protocol design that focuses on the efficiency and a robust routing of data. To respond to such needs, the IETF developed a standardized routing protocol for 6LoWPAN networks called RPL (IPv6 routing protocol for low power and lossy networks) (Lamaazi, Benamar, Imaduddin, & Jara, 2015). RPL overcomes the limitations of constrained devices, and it can adapt to the variation of the node and link metrics over time. In LLNs, nodes can have one or more parent that forms a route to the root. In RPL, the choice of the best parents is based on an objective function that uses a set of metrics. These metrics can be node-centric metrics such as energy, hop count or link-based metrics such as the expected transmission count (ETX) and the link quality level (LQL) (Kim & Barthel, 2012). However, the use of a single metric as implemented in the standard objective function MRHOF and OF0 comes with many limitations (Lamaazi, Benamar, & Jara, 2017b) (Sharma & Jayavignesh, 2015). Although a single metric based algorithm may choose the best parent for a node by considering the lowest expected transmission count value, this will induce more power consumption in the node. Thus, a single metric approach does not take into consideration all relevant parameters. In this paper, we present a new objective function called: objective function based on combined metrics using fuzzy logic (OF-EC). The present work differs from our previous works and contributions (Lamaazi et al., 2015) (Lamaazi et al., 2017b) (Lamaazi, Benamar, & Jara, 2017a) by introducing an enhancement to the standard RPL through the development of a new objective function. After the analysis of both MRHOF and OF0 presented in a previous work (Lamaazi et al., 2017b), we noticed some performance limitations of RPL essentially caused by the use of a single metric in the process of calculating the best path. The primary purpose of our new OF-EC is to select the best path to the sink node based on better criteria than the standard objective functions. The idea behind our proposal is to combine node and link metrics namely ETX, Hop Count, and Energy Consumption using fuzzy logic methods. Our method uses a membership function that allows applying a strict characterization of the quality of the chosen neighbor nodes. The inspiration for the design of OF-EC is derived from the need to satisfy different requirements of LLNs, such as real-time and reliable applications. To show the improvement that OF-EC provides, we compare it to the standard MRHOF and to the ENTOT that use the ETX link metric and the total Energy consumption respectively (FABIO, 2012). Additionally, to distinguish the efficiency of the proposed OF-EC, we compare it with OF_FUZZY (an objective function that combines ETX, Latency and remaining power using fuzzy logic) (Kamgueu, Nataf, & Djotio, 2015).

The remainder of the paper is organized as follows: Section 2 provides an overview of RPL and objective functions. Section 3 describes some research and studies related to RPL performance and Objective Functions. Section 4 serves as an introduction to the problem statement and presents the main contributions of this study. In Section 5, fuzzy logical functions and the different routing metrics are discussed. A comprehensive analysis of the results is described in section 6. Future research directions are illustrated in Section 7. Finally, section 8 concludes the paper.

II. PRELIMINARIES

In this section, we present the necessary background discussion of both RPL and Objective Functions.

a) RPL Routing Protocol

To overcome the challenges of connected lightweight devices, the ROLL working group from IETF has specified an IPv6 routing protocol for Low Power and Lossy networks called RPL(Gaston Lorente, Lemmens, Carlier, Braeken, & Steenhaut, 2017) (Di Marco, Athanasiou, Mekikis, & Fischione, 2016). It is considered an IPV6 distance vector proactive routing protocol (Yassein, Aljawarneh, & Masa'deh, 2016). RPL allows to constrained devices that are limited in terms of battery lifetime, memory and have a weak link quality to be connected to the Internet. It can support three types of communication: Point-to-multipoint, Multipoint-to-point, and point-to-point. The specificity of RPL relies on the concept of Directed Acyclic Graphs (DAGs) (Zhao, Chong, & Chan, 2016) (Tennina et al., 2016). To build the default route between nodes, the DAG defines a tree structure where nodes can have more than one parent. Moreover, nodes are organized as Destination-Oriented DAGs (DODAGs) (Oliveira & Vazão, 2015) where sink nodes act as the root of the DAGs. Toward roots, nodes form the default route based on the best parent (Iova, Theoleyre, & Noel, 2015). RPL allows exchanging information of DODAG via a set of ICMPv6 control messages defined as follows (Lamaazi et al., 2015) (Fotouhi, Moreira, Alves, & Yomsi, 2017):

- **DODAG Information Object (DIO):** initiated by the LBR (LowPAN Border Router) and retransmitted in multicast by its neighbors. It may store information like the current Rank of a node, the current RPL Instance, the IPv6 address of the root, etc.
- **Destination Advertisement Object (DAO):** used to propagate destination information upwards along the DODAG.
- **DODAG Information Solicitation (DIS):** makes it possible for a node to solicit a DODAG information object (DIO) from a reachable neighbor.
- **Destination Advertisement Object Acknowledgement (DAO-ACK):** is sent by a DAO recipient in response to a DAO message.

The following schema explains the processes when a node receives DIO messages and how it calculates the new rank. These operations allow selecting the best parents between candidates. The parent with the smaller rank is considered the optimal.

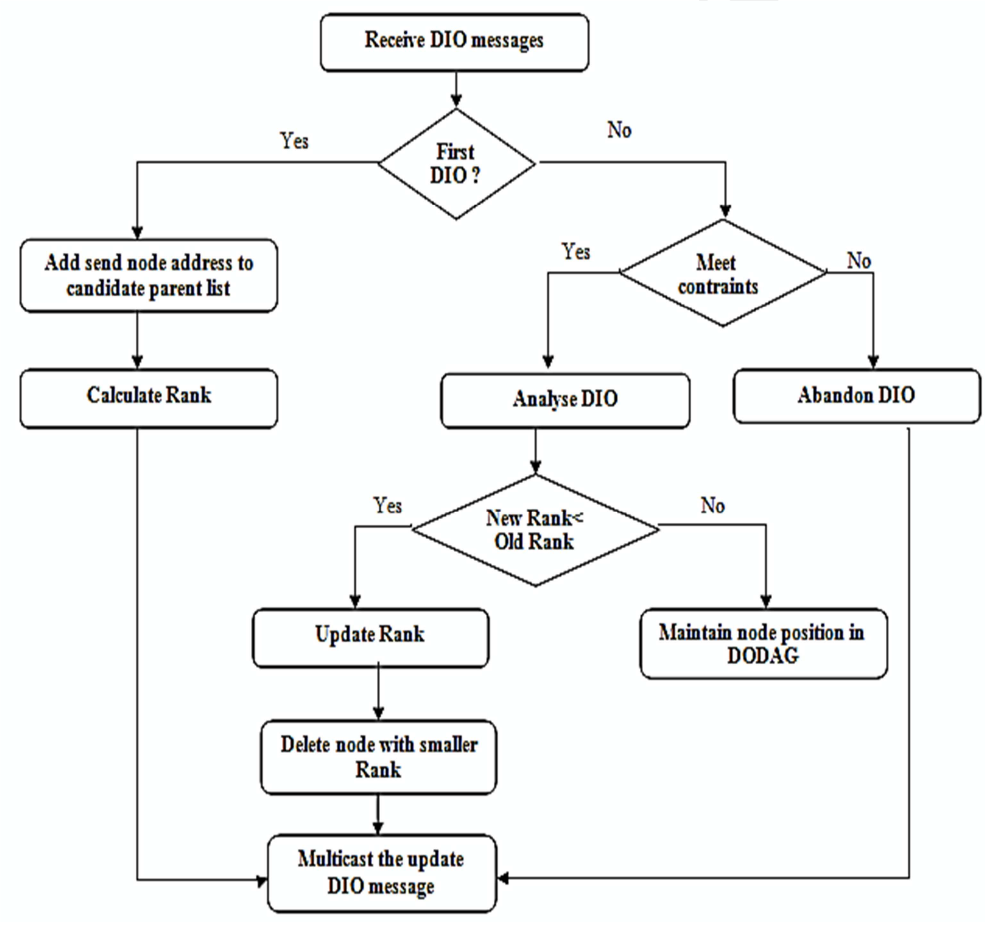

Fig. 1. Different Operations performed after receiving a DIO and the process of rank calculation in RPL

b) Objective Function

One of the main advantages of RPL is its use of the Objective Function to build route toward the destination to successfully complete the communication (H. Ali, A. Ali, & M. Badawy, 2015). The OF is considered as the key factor to specify the preferred parent of nodes (Todoli-Ferrandis, Santonja-Climent, Sempere-Paya, & Silvestre-Blanes, 2016). In a big and dense network where the nodes can have more than one parent, the OF plays a fundamental role in selecting which parent is adequate for a given node. It translates one or more metrics into a rank (position of the node in a DODAG) value, which allows selecting the best parent based on the least rank from the candidate nodes (Lamaazi, Benamar, Imaduddin, & Jara, 2016). Additionally, the OF chooses the best parent by employing a set of criteria of routing metrics, which can consider link and/or node metrics (Kim & Barthel, 2012). The implementation of the OF in the core of RPL allows the designers to specify these metrics with regards to their needs. To this date, the ROLL working group has standardized two main OFs, namely: MRHOF (Minimum Rank with Hysteresis Objective Function) and OF0 (Objective Function Zero). The OF0 selects the best parent based on the minimum hop count (HC) that it provides while MRHOF chooses the suitable route based on the Expected Transmission Count metric (ETX). The minimum value of this metric means the route is optimal to reach the destination. Table 1 shows the different metrics used by the OF:

Table 1: Different node and link metrics used by objective function

Node metrics	***Energy***	The Energy spent or remained in the network
	Hop Count	The number of hop between nodes and their destination.
Link metrics	***Throughput***	The number of bytes per second the sending node is enabled to send or receive
	Latency	The time between the sending and the reception of a packet.
	Link Quality Level (LQL)	This metric measures the link reliability using a discrete value, from 0 to 7, where 0 means the quality level of the link is unknown, 1 is the maximum level, and 7 the minimum.
	Expected Transmission Count (ETX)	The number of retransmitted packet needed before it is successfully received at the destination.

III. Related Works

There are many research studies conducted in the context of improving the RPL routing protocol, using a set of methods such as fuzzy logic to optimize the objective function (Kamgueu et al., 2015) (Gaddour, Koubâa, & Abid, 2015). This optimization can use single or multiple metrics to choose the route based on the best decision. The choice of an optimal objective function is influenced by both user and application requirements. Reviews of the previous studies concluded that some objective functions provide some limitations mainly when it is based on a single metric. For instance, the use of a link metric such as ETX can choose the best parent of nodes that provide the lowest ETX, though the nodes consume more energy.

To respond to the constrained application requirements that use RPL as routing protocol, authors in (Kamgueu et al., 2015) tried to optimize this protocol by improving the metrics used in its objective function. They used a fuzzy logic based model that combines several metrics, which are Expected Transmission Count, Delay, and the remaining energy to build the route toward the final destination. The new OF-FUZZY is compared to the standardized OF that use ETX as a metric. The results show that the new OF provides better performance in terms of packet reception rate and energy distribution which increase when the network experiences heavy data traffic. This proposal is compared with the standard MRHOF that uses single metric only but not with other proposals that use a combination or multiple metrics, which limits its efficiency.

In (Gaddour et al., 2015), authors designed a new Objective Function (OF-FL) that combines several metrics based on fuzzy logic methods. This method uses fuzzy parameters that allow the configuring of a routing decision. In comparison with the existing objective function, the OF-FL is based on a combination of four nodes and link metrics to select the best paths to the destination. These metrics are ETX, hop count, end-to-end delay and battery level. Simulation results reveal that RPL based OF-FL provides an enhancement of the protocol in terms of delay, packets loss, and network lifetime compared to the standardized OF. However, this proposal is only compared to the standard OF.

In (Kamgueu et al., 2013), authors proposed a new objective function (OF) based on a single metric which is the remaining energy. In contrast to the traditional objective function that uses link metrics as a single criterion (ex. MRHOF based on Expected Transmission Count) to select the next hop toward the destination, this new OF uses a node metric. The results show that the proposed OF-Energy equalize the distribution of energy between all nodes with a transmission accuracy. Additionally, this OF allows increasing the lifetime of the network. However, the use of this single metric is not efficient because it does not consider the link quality of the network.

In (Agarkhed, 2017), authors used the fuzzy logic method for Cluster Head selection. The primary process of this proposal is to apply the fuzzy logic method to select cluster head after the division of the cluster into sub-clusters. The comparison has been made with LEACH and CHEF approaches. Simulation results showed that the proposed method improves the performance in terms of lifetime and energy consumption. It allows the reduction of the energy consumption and maximizes the lifetime of the network. However, this approach does not consider the case where more than one Cluster Header is used, which provides more overhead and causes sensor nodes death.

In (Sharkawy, Khattab, & Elsayed, 2014), authors proposed an optimized objective function of RPL that considers a context-awareness. The developed OF was called Context-Aware Objective Function (CAOF). Their optimized function takes into consideration the limited resources of sensor nodes and their temporal changes. Moreover, CAOF has as a primary objective to take into account the battery level in the routing decision, to optimize the power exploitation. The results show that the proposed objective function increases the lifetime compared to non-context-aware RPL OFs by up to 44%. Additionally, CAOF improves the delivery ratio and guarantees more fairness in terms of battery exploitation for different nodes than non-context-aware OFs of RPL. This new proposal is limited to the improvement of the lifetime by considering the sensor resources and their temporal regardless of the network traffic and congestion. However, the study has not been extended to the mobile environment, which limits its effectiveness.

To equalize the distribution of energy among nodes with an extension of network lifetime, authors in (Nurmio, Nigussie, & Poellabauer, 2015) proposed two objective functions named respectively Parent Energy Objective Function (PEOF) and (PEOF2) which consider both ETX and the remaining energy as routing metrics to select the best parent. PEOF considers one hop and then selects the parent based on the remaining energy and ETX while PEOF2 use the remaining energy of all parents at each hop along the path. The simulation is evaluated with symmetric and asymmetric dense network. The simulation results show that PEOF2 provides more lifetime for the first node to die than PEOF and ETX. Moreover, both PEOF and PEOF2 distribute the energy equally among the nodes while they act similarly to MRHOF when considering the packet delivery ratio. In addition, authors in (Shakya, Mani, & Crespi, 2017) proposed a new objective function called SEEOF. It aims to provide energy efficiency and to extend the network lifetime. SEEOF uses an additive combination of both ETX and energy consumption. As a result, SEEOF and compared to the standard MRHOF improves the network lifetime by up to 27%. Furthermore, it allows making the energy consumed by nodes more uniformly, which keeps them alive for long duration. The proposed SEEOF improves the protocol performances but it is compared only to the standard MRHOF, which keeps its efficiency unknown against candidate proposals.
Another enhancement of the objective function using a mix of routing metrics has been proposed in (Yunis & Dujovne, 2014). Authors suggested the combination of hop count (HC), Remaining Energy

(ENG), Expected Transmission Count (ETX) and Packet Forward Indicator (PFI). The evaluation has been made by considering latency, energy consumption, and packet loss. The results reveal that the combination of ENG and HC reduce the power consumption with no impact on the latency and packet loss. Additionally, authors concluded that the HC is necessary for any combination to route packets toward DODAGs root. Additionally, every single metric has an impact on the construction of the route. Firstly, the HC only can reduce packet loss, energy and latency while with PFI only all nodes can survive which means there are no packets lost. In this case, when a node is lost, it can be detected if only there are no retransmissions from the parent node. At least the use of ENG alone does not consider the destination when nodes built the route. In summary, ENG or PFI minimize the performance, but does not take into account the path to the DODAG root.

The main difference between our proposition and the previous ones (Kamgueu et al., 2015) (Gaddour et al., 2015) explained above, is that the majority of the metric combinations are based on the remaining energy of nodes while in our case we suggest using the energy consumption of nodes as a condition to select the best parents. The primary reason behind our choice is that we can not evaluate the remaining energy if we do not know the amount of the energy consumption. However, we can estimate the energy consumption according to a set of parameters: the battery capacity, the transmission, and reception range. To make this suggestion applicable we use the fuzzy logic method to combine the ETX and the energy consumption, and we keep the hop count metric to guide nodes to the DODAGs route.

Table 2: summary of different recent works related to the use of single or/and combination of metrics

Objective Function	Metrics	Method	Improvement	Shortcoming
OF-FUZZY (Kamgueu et al., 2015)	ETX, Delay, Remaining Energy	Fuzzy logic Combination	best PDR and delay equalize energy distribution	Compared only to MRHOF
OF-FL (Gaddour et al., 2015)	delay, hop count, ETX, and LQL	Fuzzy logic	Low delay Low packet lost in high density Equalize energy distribution	Compared only to MRHOF and OF0
OF-Energy (Kamgueu et al., 2013)	Remaining Energy	Single metric	Equalizing the distribution of energy	More packet loss
LEACH-FUZZY (Agarkhed, 2017)	Battery level, Crowdedness, Distance	Fuzzy clustering	Reduce energy consumption Maximize the lifetime	More overhead Death of sensor nodes
CAOF (Sharkawy et al., 2014)	nodes' capabilities, resources, and location	Context-Awareness	Best delivery ratio, Increase network lifetime, fairness in resource exploitation	Compared only to OF0
PEOF **PEOF2** (Nurmio et al., 2015)	ETX, remaining energy	Combination	extended the lifetime equalized the energy consumption	Similar packet delivery ratio than MRHOF Compared only to the standard MRHOF
ENG+HC (Yunis & Dujovne, 2014)	HC, Remaining Energy, ETX, PFI	Combination and single metrics	Comb ENG and HC: reduce power and lost packet 100% ENG: not consider the destination 100% HC: minimize latency, energy efficiency, and PDR 100% PFI: in lost packet no retransmission is guaranteed	No consideration of link metrics
SEEOF (Sha kya	ETX and Energy Consumption	Additive combination	27% lifetime improvement equalized the energy consumption	Compared only to MRHOF

et al., 2017)				

IV. Problem Statement, Motivation and contribution

a) Problem statement

To optimize the route or to select the suitable one for nodes to reach the destination, RPL uses the objective function. The use of the OF is performed according to the user or the application requirements. The standardized OFs (OF0 and MRHOF) both use different ways to choose the path, but both of them still use a single metric: HC and ETX respectively. The use of these OFs has some advantages, such as the best parent choice, the routing table organization but still, it shows some limitations. Indeed, a single metric approach can improve some performances but may degrade others, which allows concluding that the single metric approach does not satisfy all the application requirements(Kamgueu et al., 2013) (Yunis & Dujovne, 2014). Based on the node metric, OF0 can provide a lousy quality of the link while with MRHOF, nodes offer a better one, but may lead to more energy consumption. For these reasons, we propose a combination of both link and node metrics namely ETX, Hop Count, and Energy Consumption (EC) (Lamaazi & Benamar, 2017). This combination considers both link quality and energy consumption of nodes while the hop count is used to redirect nodes to root. This new proposition allows the OF to make the right decision for the choice of the best path which improves RPL performances and the quality of services of networks (Md Zin, Badrul Anuar, Mat Kiah, & Ahmedy, 2015).

b) Motivation

The idea behind the use of combined metrics comes from the limitations that a single metric provides. In contrast to (Kamgueu et al., 2015) (Kamgueu et al., 2013) (Nurmio et al., 2015) that consider the residual energy as the node-centric metric to calculate the path, we choose in our approach to combine the energy consumption (EC) spent by nodes during their communication in the network with the ETX link metric. The remaining energy metric is defined as the energy that resides or still in the nodes. There is only two main ways to calculate the remaining energy; the first one is to consider the use of batter voltage to determine the state of charge while the second one is to observe the energy consumption of nodes over the time and then apply the following formula (1):

$$Remaining\ energy = Total\ energy - Energy\ consumption \qquad (1)$$

While the energy consumption is computed as the sum of the energy spent in transmission and reception modes.

$$EC = EC\_Transmission + EC\_Listen \qquad (2)$$

To make our proposal faster and optimal, we have considered the energy consumption where the proposed OF sums the energy consumed by nodes of a predetermined path and then select the best one. For this reason, we defined the estimated energy consumption for a selected path as the sum of the energy consumed from the current node, k, $(EC_{\_node}(k))$ and the total energy consumed by nodes between, k, $(\sum_{n=0}^{N} EC_{\_node}(n))$ and the sink . The formula (3) adopted for the estimated path is as follows:

$$Estimated\_Energy\_Consumption = EC_{\_node}(k) + \sum_{n=0}^{N} EC_{\_node}(n) \qquad (3)$$

Where "N" is the number of nodes between k and the sink. The path with less total energy consumption is considered as the preferred path toward destination. The use of the hop count metric has as its primary function, the redirection of nodes toward the destination. As we are dealing with tiny devices in LLN, one of the primary goals of any routing protocol should take into consideration the reduction of the energy consumption and the increase of the node lifetime in the network. Hence, the energy consumption is the primary criterion that should be considered for the best parent choice. To reduce the consumption of the energy, the radio transceiver uses the sleep and wake-up modes to conserve the node energy. It should sleep for a long duration and then wake-up to receive information from neighbors. There are three states: listening, receiving and transmitting. In the listening state, the transceiver consumes more power when it checks if there are any ongoing transmissions from the neighbors in the network. To conserve its power, it should turn off for a specific amount of time. However, this option may lead to the loss of valuable information. To control the wake-up process, the use of a duty cycle mechanism becomes a necessity. ContikiMAC is an implementation of the duty cycle in Contiki Operating System (Community, n.d.) where the wake-up step is performed periodically during the communication. Moreover, Contiki provides a *Powertrace* tool based on the energetic model to evaluate the energy consumption. This tool allows designing a new metric called the Total Energy Consumed routing metric (ENTOT) (FABIO, 2012). This metric allows calculating the total energy consumed by all nodes, and according to the less value of this metric, it selects the preferred parent. ENTOT tries to make a balance between the energy consumption by nodes in the network. Nevertheless, this solution is not efficient since it only considers the node based metric and not those based on the link, which may provide a bad link quality of the routes.

c) Contribution

In this paper, we combine the energy consumption metric (ENTOT) with the ETX metric, and we keep the hop count to redirect the node toward the root. To make this combination possible, we apply the fuzzy logic method. This method allows combining several routing metrics based on the fuzzy logic rules. The combination provides a new objective function called OF-EC (objective function based combined metric using fuzzy logic method). The major challenge for objective function based combined metrics in the routing protocol is to provide an appropriate rule for measuring the quality of the routes. Moreover, in our case, the rules can be distributed in such a way that the optimal routes should provide low ETX and low energy consumption. The main contribution of this work can be summarized as follows:

1. We present the shortcoming and/or limitations of recent proposed enhancements of the objective function and we propose a new combination of metrics using the fuzzy logic method that uses both ETX and energy consumption as the main metrics as well as the Hop Count to redirect nodes in the network.
2. We simulate our proposed combination with the existing OF that uses the same routing metrics but as a single one to demonstrate the enhancement of RPL.
3. We also compare our OF-EC with another objective function that uses a combination based on the same method to demonstrate the efficiency of our proposal.

Figure 2 illustrates how the nodes select the optimal path based on the combination of ETX and EC. The process of selecting the parent considers the small value of ETX as the link metric and the low energy consumption as the node metric. In the case of combination, nodes follow the path that provides the best values of both ETX and EC. In the proposed example, N1 provides an ETX equal to 20 and EC equal to 30 while N2 has an ETX equal to 10 and an EC equal to 70. If we consider the metrics separately, N2 has the lowest ETX while N1 has the lowest EC. If we consider the single metrics, a node chooses N2 as the best parent if he considers the ETX or chooses N1 if he considers

EC. In our case, nodes choose N1 because it provides the optimal combination of both ETX and EC while N2 provides a very high energy consumption, which is not efficient.

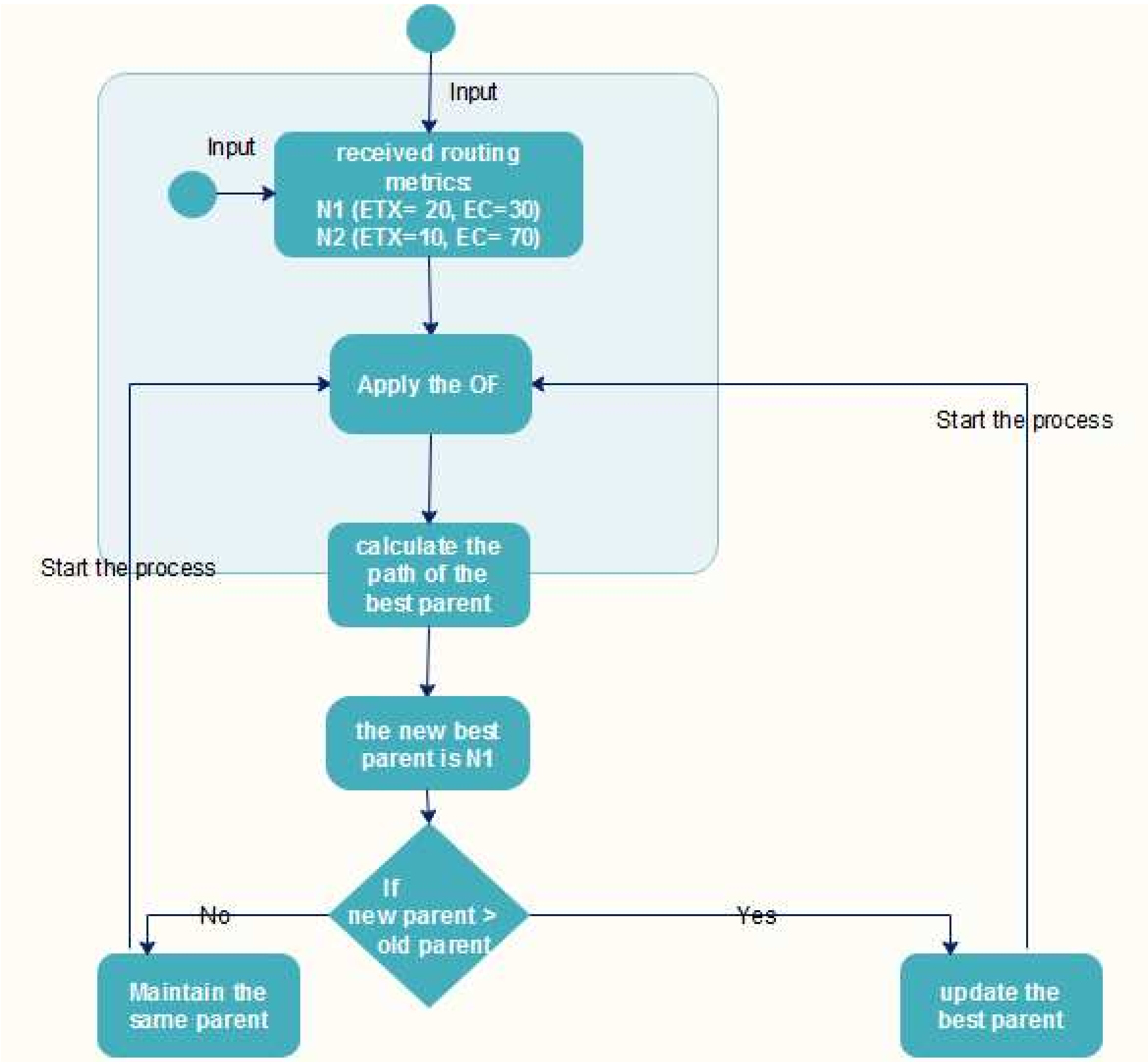

Fig. 2. Flowchart description of the best parent choice based on combined metrics.

V. Fuzzy Logic method: design and features

a) Fuzzy Logic method

The use of fuzzy logic method plays an important role when it comes to combining routing metrics. It allows converting a set of input variables such as ETX and EC into one output variable. To make this decision possible, there are some mandatory steps to follow, which are illustrated in the figure 3:

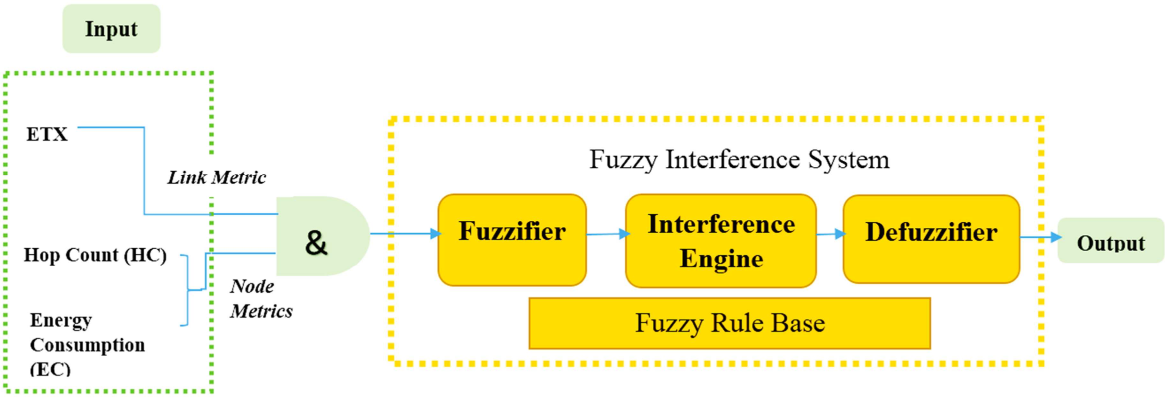

Fig. 3. Process of Fuzzy Interference System (FIS) applied to output metric

- *Fuzzification*: take a predetermined input variable and specify its membership degree (fuzziness) for fuzzy sets.
- *Fuzzy inference*: allows combining fuzzified inputs and then calculating the output.
- *Aggregation*: unifies the outputs if they depend on more than one rule.
- *Defuzzification*: transforms the fuzzy output into a determined value.

b) Linguistic variables

To extrapolate the mechanism of the fuzzy logic combination, we consider two routing metrics, ETX and EC. These metrics are represented as a linguistic variable:

ETX: number of expected transmissions count needed for a packet to successfully reached the destination.

Energy Consumption (EC): is the energy of nodes spent during the exchange of information in the network.

The main concept of the fuzzy logic is that the variables are between true or false. It takes a linguistic value instead of a numerical one. Using fuzzy logic, we can define three sets of the ETX using only the linguistic variables and which express the different stats of this metric: *short* (1 successful transmission) , *avg* (average) and *long* (Maximum of transmission). As shown in figure 4, for values of ETX below 3, the membership value of "short" is equal to 1. If we consider an ETX of 6, the node is defined as out of the fuzzy subset of the parents that provide short ETX. In the range [3 - 6], the membership decreases from 1 to 0. Similarly, "Average" and "Long" follow the same logic. Likewise, we classified the energy consumption into members of three sets as shown in figure 4.

c) Fuzzification process

To illustrate the fuzzy process, we choose to combine the ETX and EC metrics. They are the input variables. The linguistic variables used to represent the ETX (input) are: *Short*, *average* and *long* and for EC: *low, medium* and *full*. Figure 4 shows the membership between this linguistic variables. The bad path is the path that provides a very high value of both ETX and EC. The small value of these two variables provides a better route.

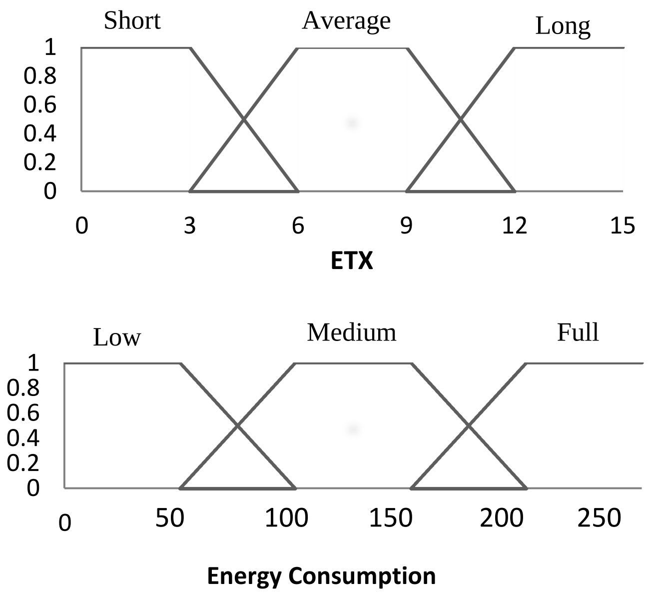

Fig. 4. Membership functions for both ETX and Energy Consumption

Table 2 illustrates the relationship between these two linguistic variables for the computation of the output variable. The more the ETX is small, and the energy is low, the better is the quality of the path.

Table 3: Fuzzy Output Metric

ETX/ Energy Consumption	Low	Medium	Full
Short	Very_good	Good	Average
Average	Good	Average	Bad
Long	Average	Bad	Very-bad

The quality of a path can be detected from the ETX and EC membership function. Following the Mamdani model (Kamgueu et al., 2015), the function of composition uses the minimum operator while the maximum is allowed to the aggregation operator. Formula 4 shows how to calculate the average quality of the link from the input (Kamgueu et al., 2015).

$$avg(quality) = max\begin{pmatrix} (\min(short(etx), full(eng)), \\ \min\big(avg(etx), avg(eng)\big), \\ \min(long(etx), low(eng))) \end{pmatrix} \qquad (4)$$

From these membership functions (see figure 5), five values of quality are provided: very-bad, bad, Average, good and very-good. These values are defuzzified in the next step to give a unique value in the output.

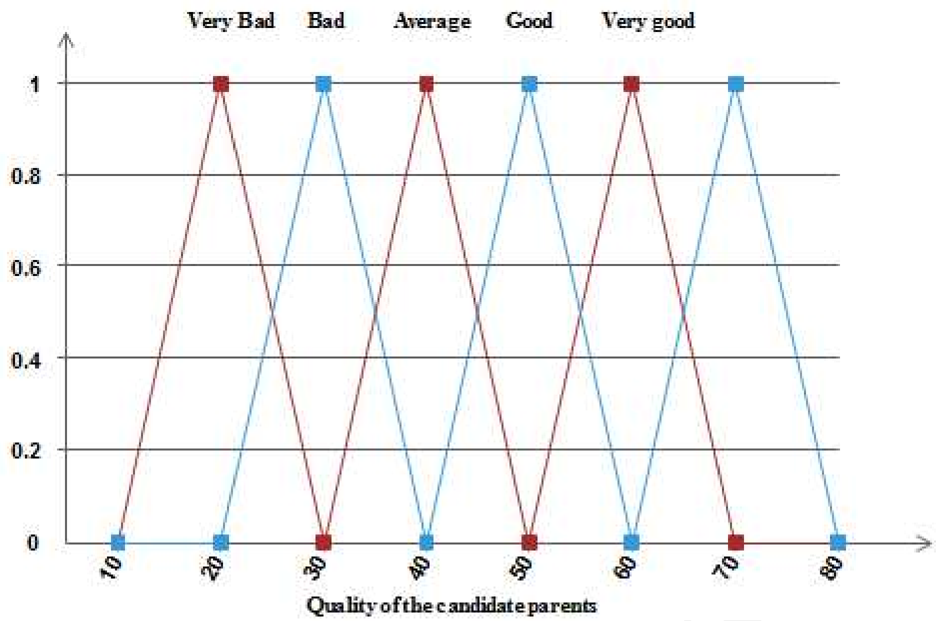

Fig. 5. Output of Membership functions of candidate parents

d) Defuzzification process

After the fuzzification step where all rules are recognized, the defuzzification step takes place. In this step, the obtained values are transformed into one crisp output metric. The most accurate and frequently used defuzzification method is the centroid that allows finding the center point of the fuzzy solution of the output membership function. In mathematics, the crisp output domain value R can be calculated, from the solution provided in region A, as follows:

$$R = \frac{\sum_{i=1}^{N} \mathrm{Wi} \times \mu\mathrm{A}(\mathrm{Wi})}{\sum_{i=1}^{N} \mu A(Wi)} \qquad (5)$$

Where N is the number of rules triggered in the inference engine, W_i is the domain value corresponding to the rule i, and nμA (W_i) is the predicate truth of that domain value.

For example, we can consider that a candidate parent has an ETX equal to 22 and an energy consumption equal to 150. According to the membership functions, the ETX is 0.3 short and 0.8 average, and the energy consumption is 0.4 low and 0.6 medium. Hence, there are two rules that are generated and only the quality "very good" and "good" are considered. The value of the rules is determined by the max-min formula (see formula 4) which gives the rule 1 equal to 0.3 and the rule 2 is equal to 0.4. The quality of the candidate parent is defuzzified according to the formula 5 and is:

$$\mathrm{R} = \frac{0.4 * 50 + \ 0.3 * \ 60}{0.4 + 0.3} = 54.28$$

Where 50 and 60 represent the centres of gravity of the quality ‘‘very good’’ and ‘‘good’’ respectively.
The implementation of the OF-EC into the core of RPL is illustrated in the two algorithms as follows:

Algorithm 1: process of OF-EC implementation

Algorithm 1 Proposed objective function combination

Input :

```
etx: Expected Transmission Count
hc: Hop Count
ec: Energy Consumption (total)
P: parent
```

Main:

```
/*For every metric*/
if FUZZY

/*calculate_etx_path_metric*/
    if p == NULL
        return ← Maximum path cost
    else
        return p ← ∑ of current etx && etx from neigbors ;
    endif

/*calculate_hopcount_path_metric*/
    if p == NULL
        return ← Maximum hop count;
    else
        return 1 + p ←.hopcount;
    endif


/*calculate_ec_path_metric*/
    if p == NULL
        return ← battery_charge_value;
    else ec = current_ec();
        return p ← ∑ of battery_charge_value && current ec;
    endif

/*calculate_fuzzy_metric: combination of etx, hc and ec*/
        return quality (etx, hc, ec);

endif /* FUZZY */
```

Algorithm 2: Rule Base of both metrics ETX and Energy Consumption as implemented into core RPL

Rule Base of (c) etx (l) energy consumption

If (etx_long and energy_cons_full) then output is very-bad;

if ((etx_long and energy_cons_medium) || (etx_avg and energy_cons_full)) then output is Bad;

if ((etx_short and energy_cons_full) || (etx_avg and energy_cons_medium) || (etx_long && energy_cons_low)) then output is Average;

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if ((etx_short && energy_cons_medium) || (etx_avg && energy_cons_low)) then output is Good;

if (etx_short && energy_cons_low) Then output is Very-good;

VI. Simulation Results of OF-EC

a) Simulation setup

To implement our proposed OF-EC, we use the COOJA simulator running on Contiki Operating System (version 2.7) (Community, n.d.) (Sitanayah, Sreenan, & Fedor, 2016). It is an open source emulator designed for IoT applications. We used the default values for all parameters, which are summarized in Table 4.

Table 4: COOJA parameters

Network simulator	COOJA under Contiki OS (2.7)
Number of nodes	10,30,50
Emulated nodes	Tmote Sky
Deployment type	Random position, grid position
Radio environment	DGRM (Directed Graph Radio Medium)
Interference range	100m
Transmit and Received ratio	TX=100%, RX=100%
Total simulations time	24h

b) Chosen Metrics

To analyze the routing protocol performances, metrics should be selected carefully to show the advantages and the limitations of each objective function. In the first step, we choose five metrics to evaluate our study.

Table 5: selected metrics for implementation analysis

Metric	Definition	Formula
Control Traffic Overhead	Total number of control messages transmitted by nodes	$\sum_{1}^{n} DIO + \sum_{1}^{n} DIS + \sum_{1}^{n} DAO$ (6)
Energy Consumption (mJ)	The energy that node spends when it exchanges the traffic in the network	(Transmit*19.5mA+Listen*21.5mA+CPU_time*1.8mA +LPM*0.0545mA)*3V/(32768) (7)
Packet Delivery Ratio	The packet delivered Ratio present the ratio of the number of received packets and the number of sent packets of nodes.	PDR (%)= total received packets at the sink/total sent packets from senders (8)
Convergence time	It is a measure of how much time needed for a node to join a DAG.	$Convergence\ time = Last\ DIO\ joined\ DAG - First\ DIO\ sent$ (9)

Latency:	It is the average time needed for a transmitted packet takes to reach sink node.	$$Latency = \frac{\sum recv_{time} - sendtime}{no.of\ hops} \quad (10)$$
Network lifetime:	- It is the duration of the first node to spend its energy and dies.	***********
The number of alive nodes:	It is the number of active nodes that still operate in the network.	***********
Preferred Parent changes:	It refers to the number of the preferred parent. That a node change during its running in the network.	***********

c) Evaluation results

To evaluate the performance of OF-EC in a dense network (from 10 to 50 nodes) with two different distributions (random and grip position), a set of metrics is considered. All our simulation figures illustrate RPL performances by considering the PDR, the Control Traffic Overhead, and the energy consumption. A comparison has been made between the standardized OF-ETX, ENTOT, OF-FUZZY and our new OF-EC that uses combined ETX and Energy consumption according to the fuzzy logic method. Figure 6, illustrates the two principal distributions adopted in this study. The results are analyzed for both cases as follows:

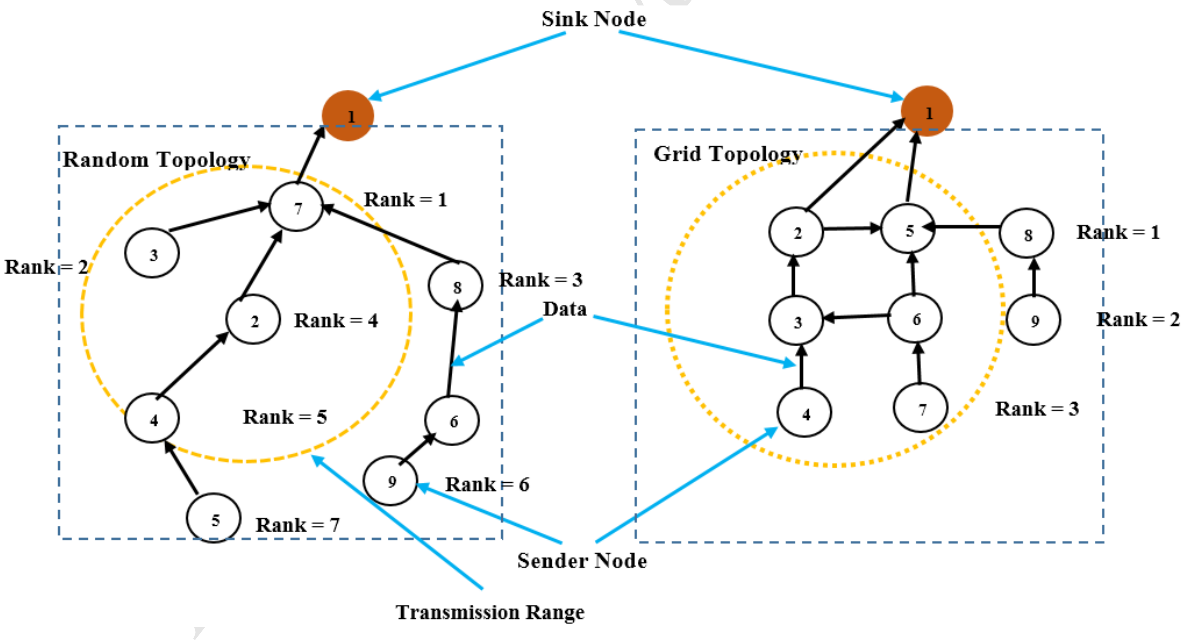


Fig. 6. Illustration of node distribution according to two main topologies: Random and Grid topologies.

1) Network density in a random topology

1.1) Latency (ms)

Figure7 shows the variation of the latency in terms of network size. OF-ETX provides higher latency when the number of nodes increases. In the case of OF-ETX, the latency is approximatively 90-217 ms higher than latency with ENTOT objective function and 100-143 ms higher than the case of OF-EC. The high value of latency indicates a lousy link quality. As mentioned in (section II. b), OF-ETX uses the expected transmission count metrics. Nodes situated far from the root exhibit more delay than those near to the root. With five retransmissions, the latency is increased compared to the case of one successful transmission. Based on the ETX metric, OF-ETX has a higher latency than ENTOT, OF-FUZZY, and OF-EC. Moreover, OF-EC still provides better metrics than OF-FUZZY. As shown in figure 7, OF-EC has a lower latency than OF-FUZZY and OF-ETX but still higher than ENTOT.

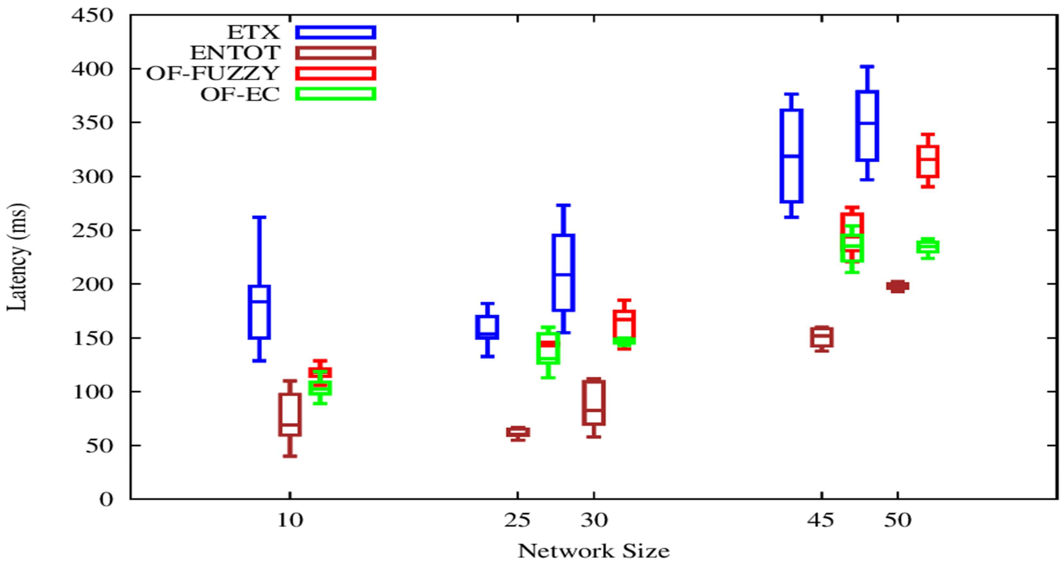


Fig. 7. Illustration of latency metric of the four objective functions in different network sizes.

1.2) Convergence time

The convergence time is calculated from the DIO messages. It is the time between the last DIO joined the DAG, and the first DIO sent. Before the nodes build the DODAG, the sink node broadcasts DIO messages, which contain its information such as DAG version, Rank, OF.... When a node receives the DIO messages from the sink node, it decides to join the DAG and then starts sending its DIO messages. This process of building the DODAG continues until receiving from candidate nodes the last DIO.

Figure 8 shows that for different network densities, OF-ETX induces longer convergence time. It takes approximately 4-5s more than ENTOT, OF-FUZZY, and OF-EC concerning five network densities: 10, 25, 30, 45 and 50. This high value is due to OF-ETX calculation. It is based on two main elements, which are the link estimator and the neighbors. The link estimator is responsible for calculating ETX for neighbors. The neighbors calculate their own ETX by collecting all ETX values in the path from the neighbors to the root. This process induces the OF-ETX to take much more time to build the DODAG. For this reason, OF-ETX provides the highest convergence time compared to ENTOT, OF-FUZZY, and OF-EC. With high-density values, ranging from 25 to 50, the OF-EC outperforms the other OFs in terms of convergence time. According to fuzzy rules (see figure 5), OF-EC uses the best combination to choose the best parent. Similarly to OF-FUZZY, OF-EC outperforms ENTOT and OF-ETX in terms of convergence time. We can deduce that an objective function that uses combined metrics improves the convergence time by 3-4 seconds in comparison to the single metric based approaches.

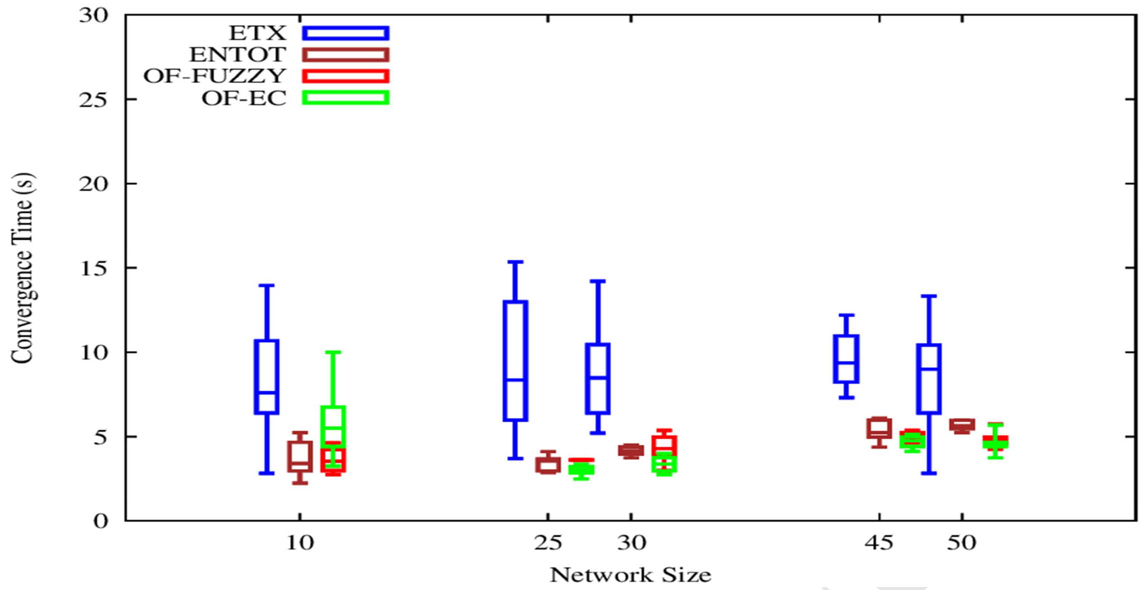


Fig. 8. Comparison of convergence time metric of the four objective function in different network sizes.

1.3) Packet delivery ratio (PDR)

To extrapolate the network reliability of OF-EC, we compare OF-EC with OF-ETX, ENTOT, and OF-FUZZY in terms of packet delivery ratio. From Figure 9 we notice that for a scalable network, ETX provides the low reliability compared to ENTOT, OF-EC, and OF-FUZZY. This result can be explained by the fact that the node selects the best parent that offer the lowest radio links even if it consumes more energy. In the case when a node consumes the totality of its energy, ETX continues to calculate the best link. This can lead to more packet loss and thus a lower PDR. Also, the ENTOT provides high PDR than OF-ETX because when a node is bottlenecks (i.e., the nodes that will be the first ones to run out of energy), it is not considered in the transmission of packets and nodes still communicate only with the alive nodes. Thus, it allows minimizing the packet loss and then improving the packet delivery ratio. In contrast, OF-ETX considers only the quality of link whatever if the node has a high or low remaining energy. Moreover, OF-EC and OF-FUZZY provide high reliability due to the use of both best links quality and the energy consumption. The high PDR refers to the use of combined metrics instead of single metrics according to the strict decision that combined metrics take to choose the best parents. Furthermore, the OF-EC outperforms the OF-ETX, ENTOT, and OF-FUZZY in terms of PDR. We justify this effectiveness by providing a low number of lost packets even if the network becomes denser.

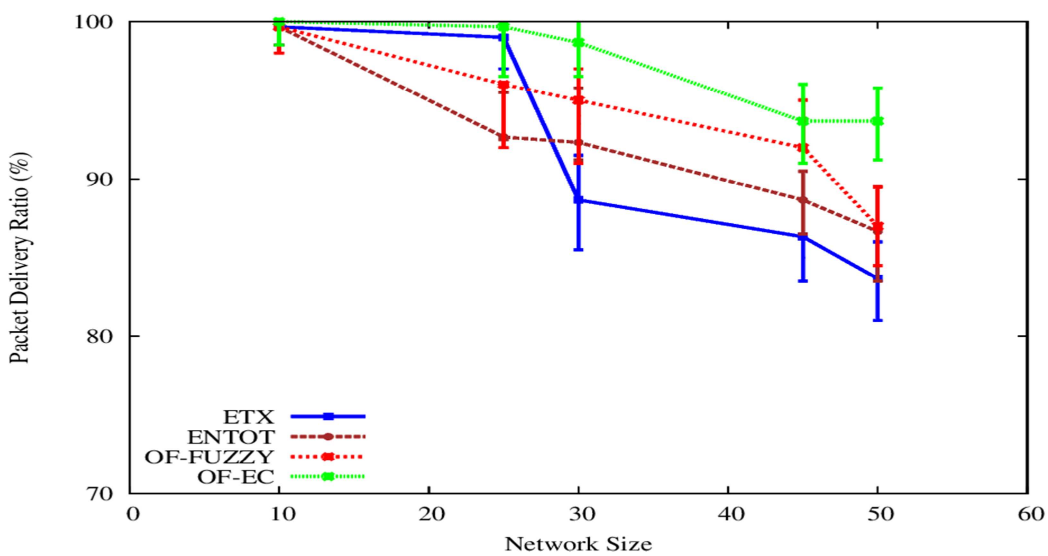


Fig. 9. Comparison of Packet Delivery Ratio metric for four objective functions in different network sizes.

1.4) Routing stability

In Figure 10, we notice that with different network sizes, an objective function that uses a single metric (OF-ETX and ENTOT) provides high control messages than objective functions with combined metrics (OF-FUZZY and OF-EC). In the case of a link failure or a bottleneck node, the network should make an update to take into consideration the available nodes. Both ETX and ENTOT are based on this update to calculate the best parent. In contrast, with combined metrics, network failures are minimized due to the use of link and node metrics in the parent selection process. An increase of the Overhead due to an increase of the number of nodes refers to the need to transmit more messages to check the availability of the candidate neighbor to select the best parent. Moreover, compared to OF-FUZZY, OF-EC provides the lowest Overhead. This is due to the use of two different metrics instead of three (OF-FUZZY). We conclude that more metrics used in the parent selection process can provide more control messages. Finally, we can show that our proposed method remains more stable than OF-ETX, ENTOT, and OF-FUZZY.

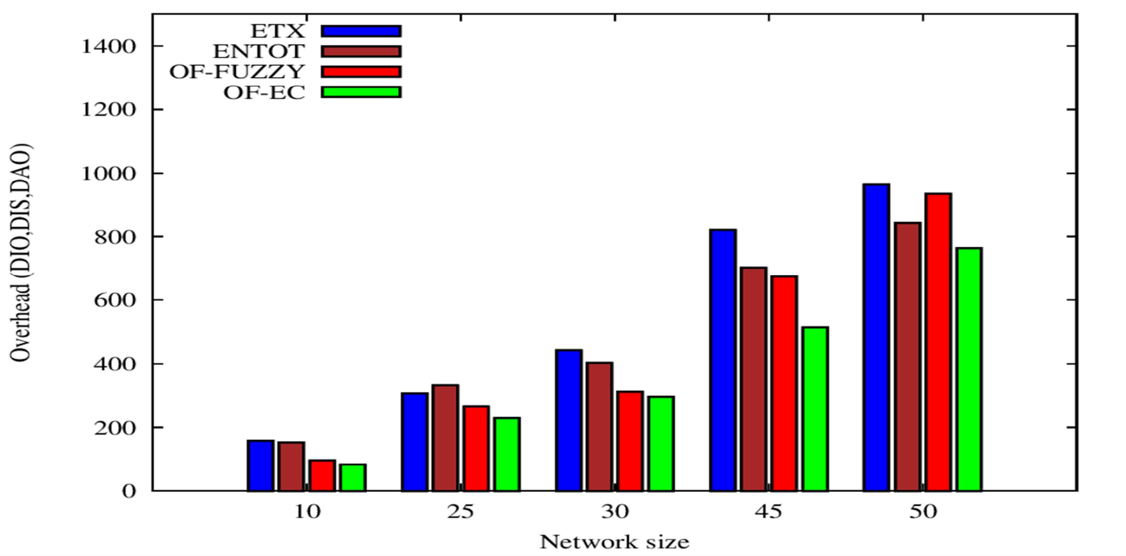
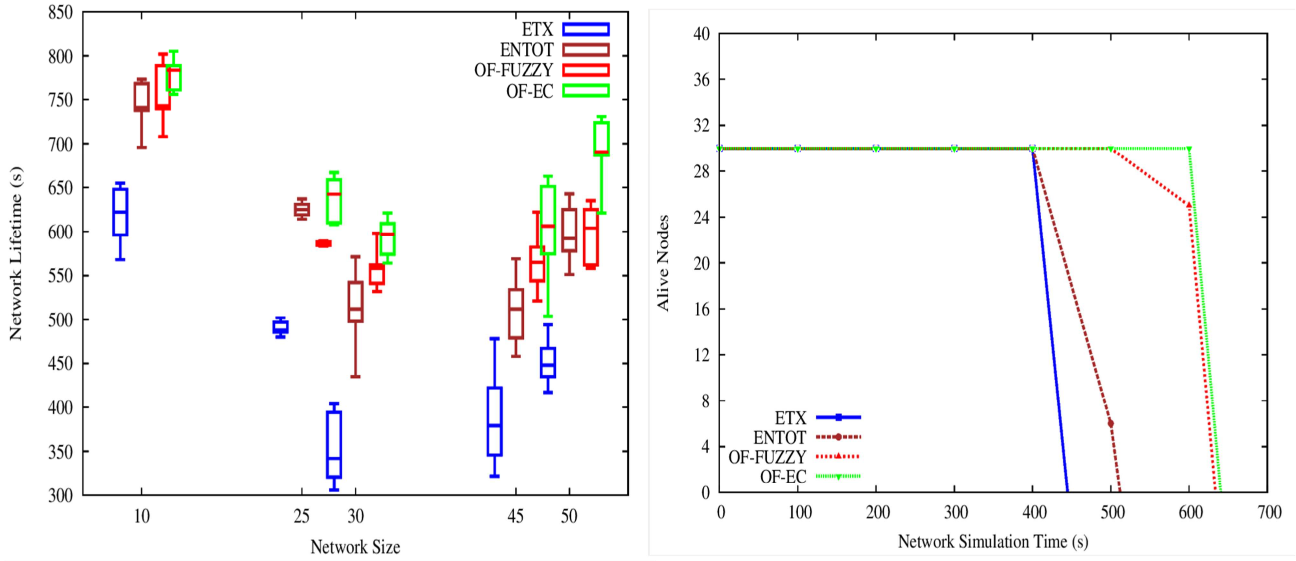


Fig. 10. Comparison between OF with ETX, ENTOT, OF-FUZZY, and OF-EC in term of the average number of control messages

1.5) Network lifetime and number of alive nodes

To record the network lifetime, we have measured the number of alive nodes until the end of simulation time. As shown in figure 11-a, OF-EC is the last objective function that runs out of the network in comparison to the other OFs. At the beginning of the simulation, all nodes use the same energy and run at the same time. Until 400s from simulation time, the four objective functions keep all nodes alive in the network. This is due to the building of the DODAG topology were nodes start to discover neighbors and exchange routing information. After this time, from 400s until the 1100s, nodes transmit the packets to the candidate neighbors to calculate the best route toward the final destination. At this time, the objective functions use their metrics for parent selection process. As shown in the figure, an objective function that uses single metrics run out much faster than those that use combined metrics namely OF-FUZZY and OF-EC. With one metrics, the nearest nodes to the destination can undergo the whole battery earlier than far nodes. These nodes failures have an impact on the network survivability and then on the lifetime metric. As shown in figure 11-b, and according to figure 11-a, that demonstrates that OF-EC keeps the node survivable more than OF-ETX, ENTOT, and OF-FUZZY. OF-EC provides a high value of a lifetime. As a conclusion, OF-EC still better in terms of the lifetime which allows to the network to operate for a long time.



a) Network lifetime **b)** Number of alive nodes

Fig. 11. Comparison of Network lifetime and number of alive nodes metrics of the four objective function in different network sizes.

1.1) Preferred parent changes

In order to assess the network stability, we compare the measured number of best parent changes of OF-EC with ETX, ENTOT and a candidate objective function: OF-FUZZY. As shown in figure 12, the number of parent changes remains relatively low for both ETX and ENTOT objective functions compared to OF-EC and OF-FUZZY. The figure illustrates a progression of the number of parent changes of all objective functions with the increase of the number of nodes. With high density from 30 to 50, both OF-EC and OF-FUZZY reveal an unstable topology due to the high value of parent changes that they induce. However, this augmentation of parent changes allows improving routing performances, which can affect positively the route quality.

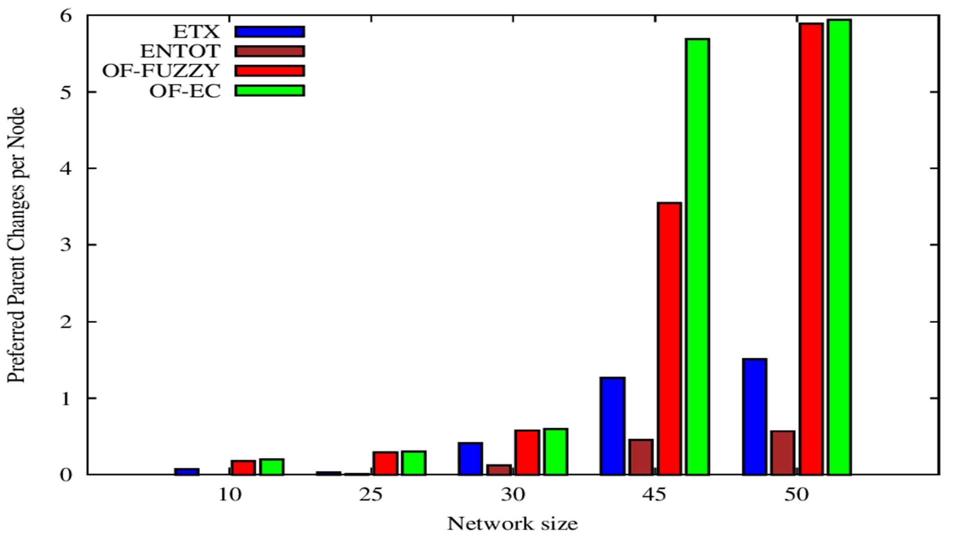


Fig. 12. Comparison of the number of preferred parent metric for four objective functions in different network sizes.

1.6) Energy Consumption

It is clear that the objective function has a direct impact on the energy consumption of the whole network [7] [6] [10]. One of the main goals of this study is to demonstrate how the energy consumption is distributed within the network. We notice, from Figure 13 that OF-EC and OF-FUZZY consume lower energy than OF-ETX and ENTOT. This result is due to the Fuzzy calculation that takes into consideration the energy of nodes and the link quality, which has an impact on the network survivability and the node failure. For this reason, we consider the energy consumption of each node in the network with a number of 30 nodes. Figure 14 illustrates the distribution of the energy consumption of the nodes along the network. We can notice that the OF-ETX, ENTOT and OF-FUZZY metrics provide high power consumption than combined metrics used in OF-EC. However, the simulation demonstrates that our proposed OF-EC has a significant impact on the distribution of the energy consumption for each node in the network during the whole simulation time. As shown in Figure 14, the distribution of the energy consumption in OF-ETX, ENTOT, and OF-FUZZY is not well balanced between all nodes. This result is due to the OF-ETX choice, which selects a route with a low ETX without considering the energy consumption of the node, while with ENTOT, it chooses the node with the lower energy consumption even if it provides a bad link quality. These reasons explain the significant benefit of the use of combined metrics with OF-EC, where nodes are selected according to their good link quality and low energy consumption. Our approach allows extending the network lifetime, and nodes can keep their energy for a long time as we proved in figure 11.

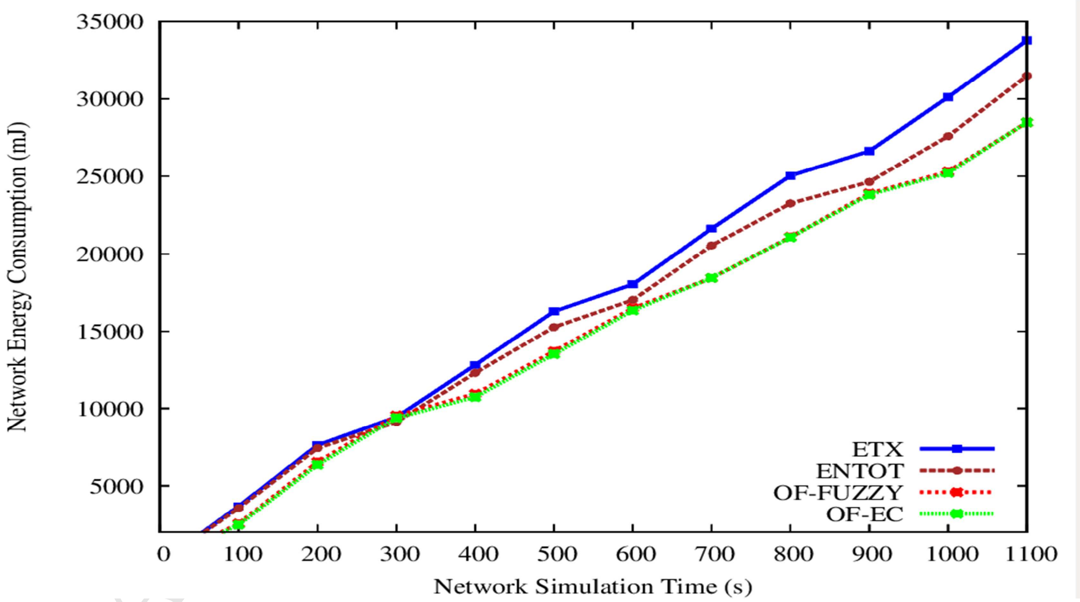


Fig. 13. Comparison between OF with ETX, ENTOT, OF-FUZZY, and OF-EC in terms of energy consumption vs. simulation time

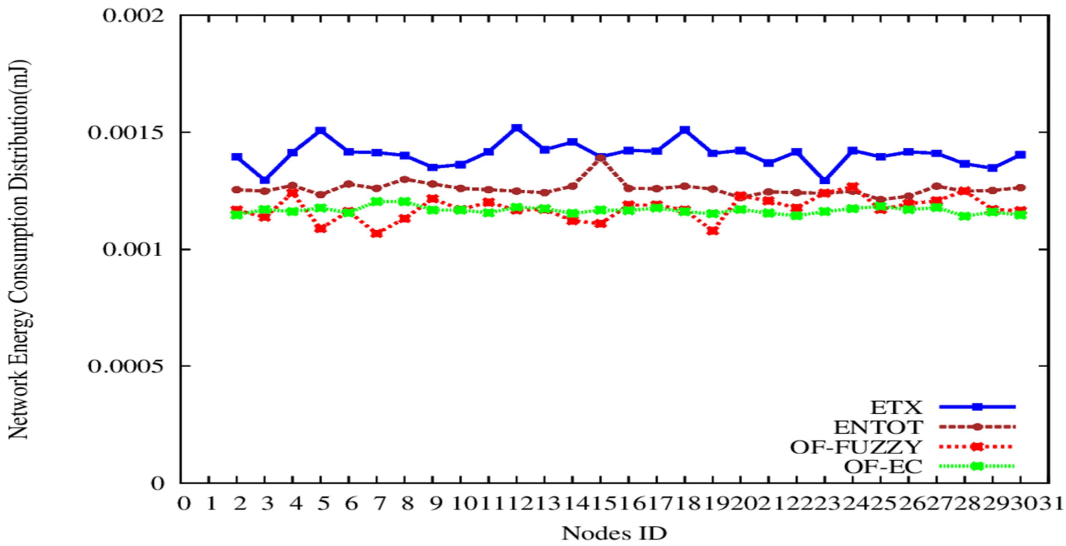


Fig. 14. Comparison between OF with ETX, ENTOT, OF-FUZZY, and OF-EC in terms of energy consumption per node

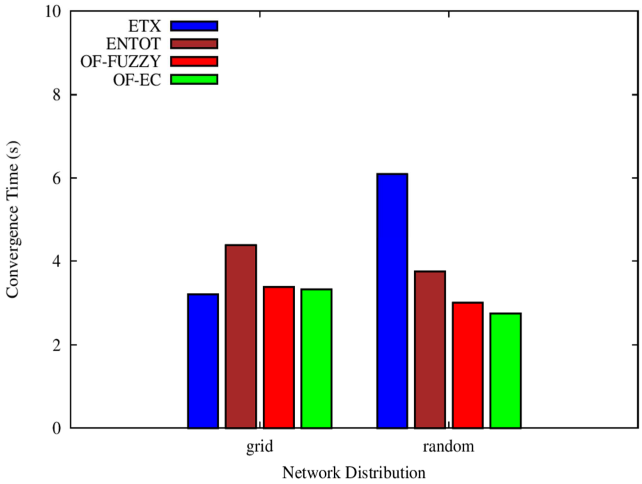
Table 6: Summary of the metrics improvement

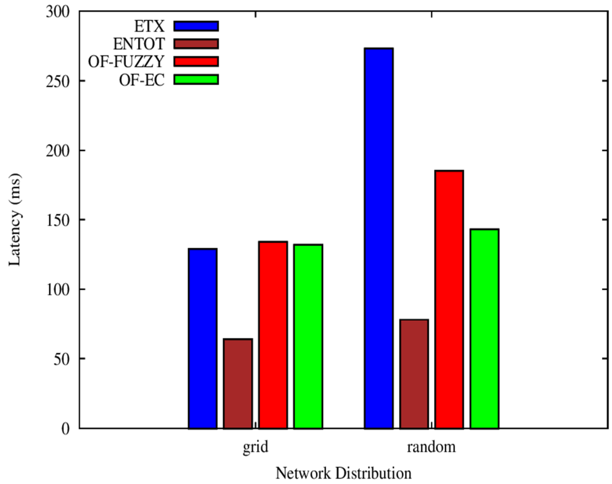
Enhancement	Latency		Convergence time		Packet delivery ratio (PDR)		Routing stability		Network lifetime	
Density	N=10	N=50	N=10	N=50	N=10	N=50	N=10	N=50	N=10	N=50
ENTOT vs standard	62%	43%,	55%,	37%	0%	3%	-3%	-14%	16%	24%
OF-FUZZY vs standard	35%	9%	53%,	46%	0%	4%	-64%	-3%	16%	25%
OF-EC vs standard	44%	32%	27%	49%	0.33%	10%	-71%	-26%	20%	35%

2) Comparison between network topologies: grid vs. random

2.1) Latency and Convergence time

In the following scenario, we evaluate the objective functions used in this study in different network topologies. We use a random and a grid distribution. Figure 15 illustrates the latency and the convergence time of OF-ETX, ENTOT, OF-FUZZY, and OF-EC. In both cases, OF-EC outperforms the other objective functions. From figure 15-a, we can notice that OF-ETX has a considerable change in terms of latency (150 ms) when the distribution varies from random to grid. Moreover, the convergence time decreases by 4-5 seconds from random topology to grid, as we show in figure 15-b. We also deduce that OF-EC is not influenced by the change of the topology since it provides a low decrease in latency (10-20 ms) and a low increase of the convergence time (2-3 s) when the network topology changes. Furthermore, figures 15-a and 15-b show that the distribution of the network has an impact on the routing performances. Some objective functions such as OF-ETX and ENTOT are affected by the change of the network topology.





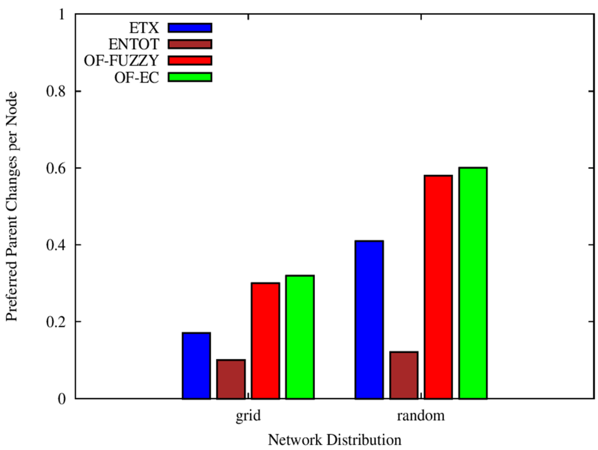
a) Convergence time in grid and random distribution

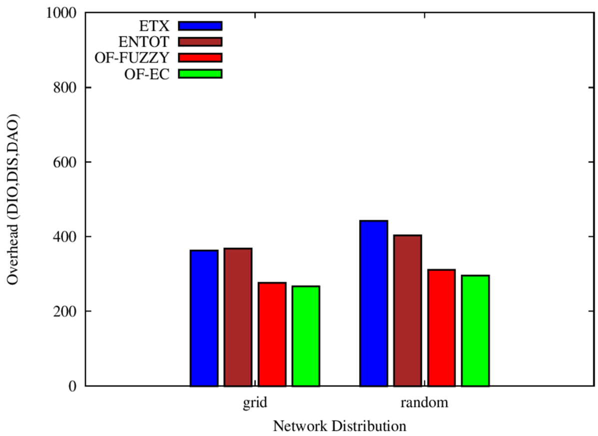
b) latency in grid and random distribution

Fig. 15. Comparison of convergence time and latency for four objective functions in different network distributions.

2.2) Preferred parent change and overhead:

Figure 16-a represents the preferred parent changes. We can deduce that the grid distribution minimizes the number of parent changes due to the nodes position. In grid topology, nodes have the same rank from the sink node while in random topology they are distributed randomly. From figure 16-b we notice that in both distributions, OF-EC provides low overhead. We also deduce that combined metrics based OFs are less impacted by topology changes in comparison to a single metric based. In random topology, OF-ETX has a high overhead value than ENTOT, OF-FUZZY, and OF-EC, while in grid topology it decreases significantly. In both distributions, OF-EC shows a lower overhead than OF-ETX, ENTOT, and OF-FUZZY, which proves the efficiency of our proposal regardless of the network topology.





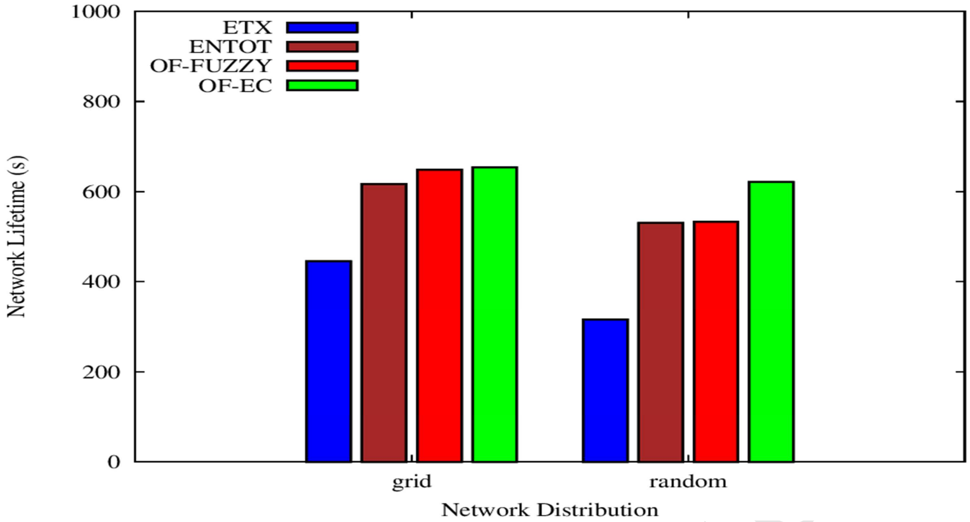
a) Preferred parent change in grid and random distribution

b) overhead in grid and random distribution

Fig. 16. Comparison of convergence time and latency for four objective functions in different network distributions.

2.3) Network lifetime:

Figure 17 shows the measured network lifetime for four OFs used in this study. Two main distributions are considered: grid and random topologies. It is clear that nodes in a grid distribution provide high lifetime than nodes in the random one. In grid topology, nodes are in the same rank with the sink. This allows reducing the packet loss, the overhead, and the energy consumption and then increasing the network lifetime. We can conclude that our OF-EC keeps its effectiveness even if the network



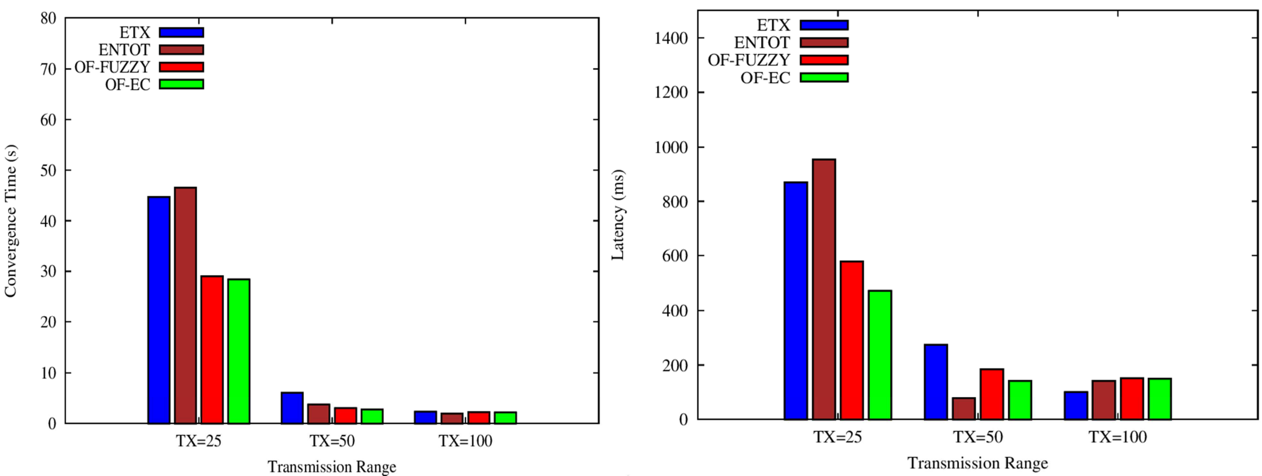
topology changes.

Fig. 17. Comparison of convergence time and latency for four objective functions in different network distributions

3) Analysis based on transmission range

3.1) Convergence time and Latency

In the following scenario, we study the impact of the transmission range on routing performances. It is clear that any change in the network topology or the transmission range can improve some performances while it can degrade others. Our goal is to assess the proposed OF-EC in this context and show if it is affected by these changes. Figure 18-a shows that with a low transmission range



(TX=25), the network takes too much time to converge (approximatively 6-40s) than TX=50 and TX=100. Also, and as shown in figure 18-b, with low transmission range, all OFs provide a higher latency, which allows concluding that in such conditions the network has a bad link quality. In contrast, with high transmission range from 50 to 100, the network has a very low latency, approximatively 150-1000 ms lower than the case of high transmission range. In all transmission range values, our proposal, OF-EC, has the lower convergence time and latency. This proves the efficiency of our proposal compared to the other OFs.

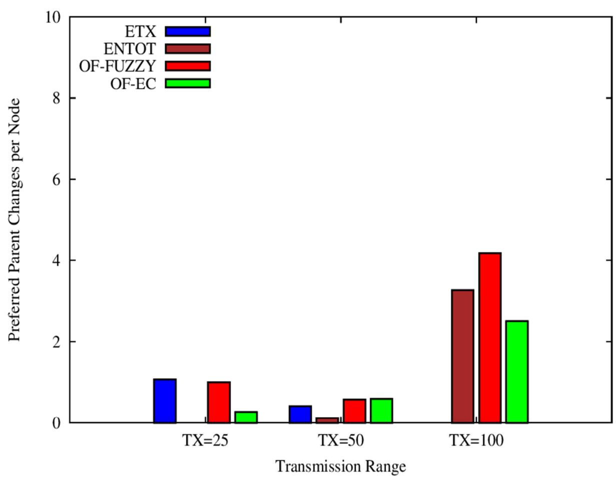
a) Convergence time in different transmission ranges b) latency in different transmission ranges

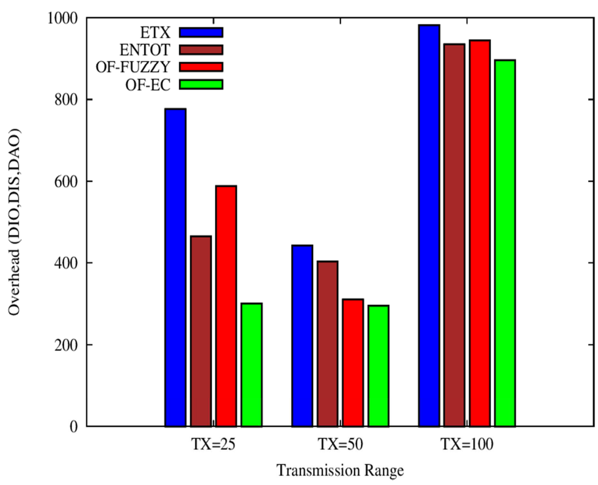
Fig. 18. Comparison of convergence time and latency of the four objective functions in different network transmission range.

3.3) Overhead and Preferred parent

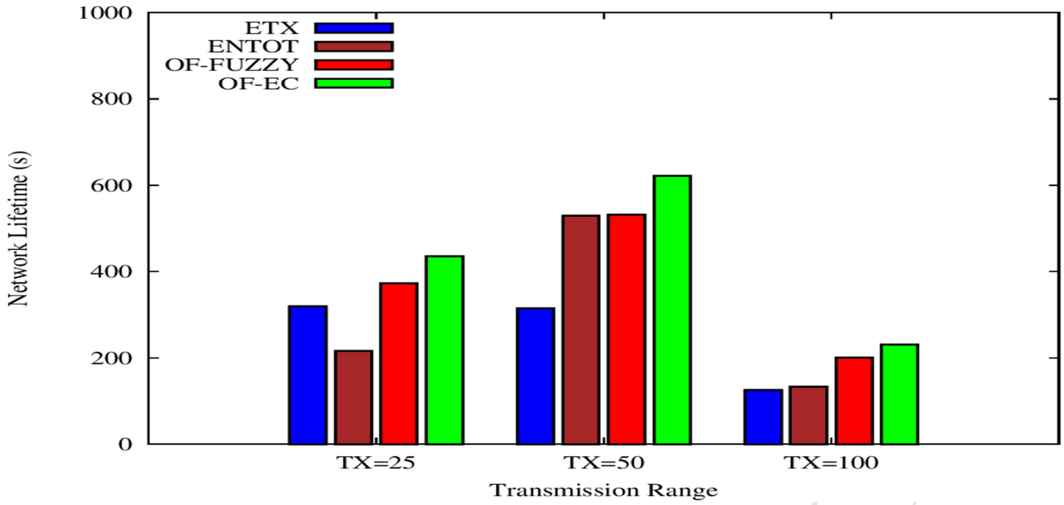
Figure 19-a presents the preferred parent changes in different transmission ranges. We see that in a high transmission range, nodes change very frequently their parents to reach the destination. We also notice that with the increase of transmission range, ENTOT increases the number of preferred parents too. In a range of 25m, ENTOT is more stable than OFs, and it does not lead to parent's change (Number of preferred parents equal to zero). Moreover, OF-EC outperforms OF-FUZZY in terms of preferred parents in a transmission range of 25m and 100m.

Figure 19-b shows the overhead variations in different transmission ranges. We notice that within a range of 50m, all OFs operate better. For all transmission range values, OF-ETX shows the highest overhead compared to ENTOT, OF-FUZZY, and OF-EC. In contrast, our proposal shows the lowest overhead value, which means that OF-EC is more stable than the other OFs even if the transmission range is changed. Additionally, the high overhead value in a range of 100m has an impact on the network lifetime. Figure 19-c shows the network lifetime for four OFs in different transmission ranges. We can notice that in high transmission ranges all OFs provide a very low lifetime, which can be justified by the fact that nodes in a high transmission range consume very quickly their resources, which leads to a shorter lifetime. For all transmission ranges values, 25m, 50m, and 100m, the network with OF-EC used survives longer than with the other network with other OFs. We can conclude that OF-EC is not affected by the change of the transmission range.





a) Preferred parent change in different transmission ranges b) overhead in different transmission ranges



C) Network lifetime in different transmission ranges

Fig. 19. Comparison of preferred parent changes and overhead for four objective functions in different network transmission ranges.

Discussion:

The extensive analysis of RPL performances assessment in this paper allows us to come up with some conclusions that we summarize as follows:

1: the specification of RPL routing protocol for LLNs allows overcoming some limitations of constrained applications. According to our study of RPL, we conclude that this protocol is very promising with regards to its flexibility with the application requirements.
- RPL is considered the most reliable and efficient protocol for LLNs requirements.

-The strength and success of RPL rely on its supports of bidirectional traffic including MP2P, P2MP, and P2P, and it allows connecting nodes to the Internet using global IPv6 addresses.

2: Our simulation results show that:

-The density of the network has a direct impact on the protocol performances; it can induce more packet loss and energy consumption. This can be explained by the fact that nodes can not easily find the best parent toward the destination with regards to the number of candidate nodes. It can also affect the alive nodes and thus network lifetime.

-the topology of the network and the transmission range can affect the protocol performances, by ameliorating some metrics and degrading others.

3: the concept of the objective function used in RPL and its implementation separately in the core of the protocol provide great flexibility for RPL to support several application requirements. Moreover, the comparison of the two standardized objective functions, OF0 and MRHOF (Lamaazi et al., 2017b) allows concluding that both objective functions can not satisfy all LLNs requirements. The use of a single metric can improve the protocol performances while degrading others.

We have demonstrated that a small change in the core of RPL specification can keep the main base of its parameters while improving its performances. For this reason, we have proposed a new objective function (OF-EC) for RPL specification. In contrast to the standard OFs that uses a single metric, OF-EC is based on combined link and node metrics (ETX, hop count, and energy consumption) using fuzzy logic methods, which is considered an adequate technique that allows combining several metrics based on fuzzy parameters. OF-EC is proposed and compared with various OFs, OF-ETX, ENTOT, and OF-FUZZY. Our solution is more efficient in terms of PDR, Overhead, Network lifetime, convergence time, latency and energy distribution and keeps its efficiency in different network topologies and with different transmission ranges.

VII. CONCLUSION

In this paper, we proposed an enhancement of the RPL routing protocol based on its objective function. The OF standardized by the IETF uses a single metric: The Hop Count for OF0 and the Expected Transmission Count for MRHOF. We proposed a new objective function based on a combination of ETX and energy consumption called OF-EC. To apply this combination, we have adopted the fuzzy logic method, which is based on fuzzy membership that determines a set of rules for the combination. The comparison has been made with various objective functions: OF-ETX, ENTOT, OF-FUZZY. The simulation results showed that the proposed new OF-EC outperforms OF-ETX, ENTOT, and OF-FUZZY in terms of PDR, network lifetime, overhead, convergence time, latency and energy consumption. Additionally, the proposed combination allows equalizing the distribution of the energy consumption of all nodes, which reduces the probability of network failure and increases nodes lifetime. Moreover, OF-EC proved its efficiency in comparison with OF-ETX, ENTOT, and OF-FUZZY even if the network topology and the transmission range change. In future works, we propose to improve RPL by considering the trickle timer.

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