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A comprehensive survey on enhancements and limitations of the RPL protocol: A focus on the objective function

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ABSTRACT

The RPL routing protocol for low power and lossy networks uses the objective function (OF) to build a Destination Oriented Directed Acyclic Graph (DODAG) based on a set of metrics and constraints. The OF has as the main function to select and specify the best parent or the optimal path to reach the destination. However, proposing an adequate objective function in Low Power and Lossy Networks (LLNs) presents a substantial challenge. In this paper, we propose a survey on existing objective functions in LLNs based on a set of metrics. These metrics can define a node or/and link characteristics. We highlight the advantages and the shortcoming of each studied solution. Furthermore, we propose a classification of the used metrics and the criteria of choice. Then, we present a comparative study of the existing OFs in terms of the required performances of the RPL protocol and we provide a deep statistical analysis of all reviewed papers. Finally, we conclude our contribution by highlighting the different issues and challenges that can be exploited for future works. We believe that this survey will help LLNs researchers' community to easily understand the objective function concept and contributes to improving RPL in this context for further relevant research works.

1. Introduction

The Internet of things (IoT) [1–3] is considered as a revolutionary technology that allows connecting everyday objects to the Internet. It covers a set of the domains such as healthcare, military, industry, monitoring, building a smart home, in the purpose to make our daily life easier and more secure [4]. The tiny devices used in IoT are lossy, low powered and have limited resources [5,6]. Hence, the use of an optimal routing protocol [7,8] in such context becomes a necessity and a challenging issue for many researchers [9,10]. The IETF ROLL working group has proposed [11] an IPv6 protocol for low power and lossy networks called RPL [12]. RPL is a promising protocol that has several advantages for tiny devices. One of its main strengths relies on its flexibility to handle and manage network topology changes and implementation modifications. Moreover, it is used to respond to LLNs requirements such as load balancing [13], unbalanced energy consumption (EC) [14] and network traffic [15]. However, one of the main issues of RPL remains in the choice of the optimal path to reach the destination. Hence, various research works have tackled this issue and proposed alternative enhancements for the best parent/ best path scenarios. The requirements of the applications of advanced technologies in IoT [16,17] lead to carefully choose an optimal path between sensors, that is fast and with low loss of information. The use of an adequate objective function (OF) can improve the routing quality. However, many scenarios can cause some problems to the LLNs applications, such as network scalability, mobility [18], security [19,20] and topology changes. Some critical scenarios can lead to more packets loss, decrease the network lifetime, increase the overhead and induce more energy consumption. In this paper, we focus on the enhancements related to the objective function (OFs) exclusively. The aim of the objective function in routing protocols is to find the optimal path to reach the destination. A good path should respond to a set of criteria: saving energy, increasing network lifetime, enabling fast convergence, providing a good link quality such as low ETX (expected transmission count), PDR (packet delivery ratio), avoiding routing loops, etc.…

The objective function has gained a lot of improvement and attracted many researchers from the LLNs community. The absence of surveys dedicated to previous works on objective function in RPL constitutes a strong motivation for us to write this paper, which has as a primary goal to present the main efforts made to

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assess and to improve the objective function that we statistically analyse in this paper.

1.1. Related surveys

To date, only few surveys have focused on various aspects of RPL. The majority of these surveys shed light on the core of RPL and its deployment in various environments to showcase its characteristics and limitations [21–23]. The primary motivation behind our survey is to focus on the objective function since it represents the main component of RPL that attracted many researchers to propose different RPL optimizations. In [21], the authors survey the history of research efforts made to improve RPL since its standardization (2012) until the year 2016. The authors focus on the RPL reputation in the research community and how it has been investigated so far in addition to the effort made by the IETF ROLL Working Group on the standardization of RPL as a solution for LLNs requirements.

Another survey [22], focuses on the routing protocols supported by Contiki OS. The authors present the Contiki OS structure and its network stacks in addition to a review of existing research based on some main topics such as RPL and Opportunistic routing. In [23], authors propose a deep analysis of the successful solutions in the literature interested in overcoming RPL limitations with regards to its core operations. The survey addressed the RPL's shortcomings, and investigates some challenges and some limits to mitigate. The survey paper presented in [24] focuses on the main features of the RPL routing protocol. It presents relevant research efforts related to the performance assessment and improvement of RPL. However, the survey does not discuss the research efforts made to overcome RPL shortcomings. Authors in [25] surveyed and analysed the most relevant extensions of RPL in mobile environment. The aim of this survey is to compare routing protocols for LLNs and to highlight the effect of mobility on network behavior. Similarly, authors in [26] present a comprehensive analysis of the mobility management in WSNs based on 6LoWPAN technology including advantages and drawbacks. However, the authors did not compare existing approaches for RPL improvement. The paper [27] can be seen as a general overview of the RPL protocol. It discusses the different components of RPL and presents a review of the performance evaluation of RPL. The paper discussed only five approaches with no mention of the composite metrics or combination approaches, which we tackle in our current survey. In [28], the authors treat the different attacks that can contaminate the 6LoWPAN and the RPL protocols operations. The authors focused only on the security aspect; with no interest in the core of RPL especially for objective function though it is the base of rank computation. Authors in [29] propose a comprehensive survey of RPL and its additional extension P2P-RPL. They present recent research studies focusing on performance assessment, challenges, and open issues of RPL. The survey describes the limitations of the RPL standard without presenting the research efforts proposed to improve both RPL and P2P. Similarly, authors in [30] propose a review of the technical insights and assessment of various implementations and optimizations of the RPL protocol. Though the survey shed light on the different RPL application fields (healthcare, smart environment, transport…), it does not cover the works related to the Objective Function, which motivated us to write the current survey. Authors in [31] highlight the different aspects of RPL regarding its implementation and domain of application to provide new challenges where they recommend the improvement of the objective function specification. Other surveys [32,127] discuss the main issues of RPL; namely unbalancing traffic and congestion issues.

Table 1 summarizes some features of the survey papers discussed in this section.

1.2. The current survey

Due to the number of published works dedicated to improving RPL based on its objective function, this survey provides an opportunity to overcome some repeated solutions and gives more inspirations on designing new objective functions according to the LLNs application requirements. In addition, the current survey allows avoiding similar combinations of routing metrics and giving a deep vision on metrics and constraints differences. Compared with existing surveys on RPL, this article is the first to focus on the main RPL component, namely the Objective Function. It also presents a comprehensive overview of the routing metrics used for rank computation. In addition, our survey presents the different approaches published so far for routing metric combinations. Then, it proposes a deep analysis based on statistics of research efforts made for objective function assessment with the aim to extrapolate the standard OFs weaknesses and shortcomings. Compared to other RPL surveys, the current work discusses the existing enhancements that allow overcoming the limitations of the objective function based on either single or composite metrics.

1.3. The scope of this survey

In this paper, we present a thoroughly comprehensive and systematic review of the studies interested in RPL improvement and limiting our study to the existing proposals related to the Objective Function. We investigate the currently existing solutions in terms of selecting routing metrics and their implementations for both single and composite metrics. We also discuss in detail the research effort proposed to overcome the objective function limitations, and we conclude with some future directions.

We summarize the main contributions of this paper below:

- We provide an exhaustive background on routing metrics used in RPL protocol and their characteristics, and we highlight the difference between a routing metric and a routing constraint.
- We present a comprehensive overview of standard objective functions, limitations, and shortcomings reported in the literature.
- We present an overview of the different approaches used for routing metrics composition used for RPL-based objective functions.
- We provide an extensive survey and an in-depth analysis of research efforts made to address the proposed assessment and enhancement of the objective function.
- We present a comparative and statistical analysis of existing RPL objective Functions.

1.4. Organization of the survey

Table 2 lists the abbreviations used in this paper. The remainder of the paper is organized in the following fashion:

Section 2 presents an overview of the routing metrics and their characteristics. Section 3 is dedicated to the RPL standard objective functions. In Section 4, we present and discuss the different approaches related to routing composition. Section 5 presents a comprehensive survey of the proposed assessments and recent enhancements of the Objective Function in the literature. In Section 6, we present a deep analysis of the different results obtained from this study. Finally, Section 7 concludes the paper.

The structure of the current survey is illustrated in Fig. 1.

2. RPL routing metrics overview

In 2012, the IETF ROLL working group proposed RPL as an IPv6 routing protocol for networks dealing with lossy links and

Table 1
Related survey papers.

Surveys related to RPL	Topics	Scope	Research effort/ Year	Common points with our survey
H. Kim et al. [21]	• Upward/Downward routing, Interoperability, • Multicast, Load Balancing, Multi sink/instatnce, • LOAD(ng), Mobility security	• how RPL has been used and evaluated in the context of LLNs; • (the success of RPL in the context of LLNs)	2012–2016	• Load Balancing, • Multi sink/instance,
Bin Zikria et al. [22]	• RPL, LOADng, • Opportunistic, Secure and Context aware routings • IPV6 neighbor discovery protocols	• Routing protocol supported by Contiki OS	2002–2017	• Context aware routing
B. Ghaleb et al. [23]	• routing maintenance/selection, • optimization mechanism, downward routing, • under-specification aspects, • RPL modes, memory limitations	• The success of the state-of-the-art solutions that were proposed in the literature to overcome RPL limitations	2011–2017	• Routing selection,
O. Gaddour et al. [24]	• Target network, Routing type, Topology, • Traffic flows, Message update, Control messages, • Neighbor discovery, Transmission, • Metrics and constraints, Modes	• RPL features	2007–2011	• Metrics and constraints.
A. Oliveira et al. [25]	• Routing protocol properties • Route discovery mechanisms. • Route maintenance mechanisms • Route repair mechanisms.	• RPL with mobility	2010–2015	–
O. Iova et al. [26]	• quality of services (QOS) • resource management • routing protocol, security, control topology	• Mobility	2005–2014	–
E. Aljarrah et al. [27]	• Destination Oriented Directed Acyclic Graph (DODAG), • Control Massages, Objective Functions (OFs), Routing modes	• RPL features	2004–2015	• Standards Objective functions
P. Pongle et al. [28]	• Selective Forwarding Attack • Sinkhole / Sybil Attacks • Hello flooding / Wormhole Attacks • Clone ID / Blackhole Attacks • Denial of Service /Alteration and spoofing attacks	• 6LoWPAN and Security of RPL	2011–2013	–
M. Zhao et al. [29]	• Applications of LLNs • RPL and P2P-RPL overview • RPL and P2P-RPL implementation • Simulation study	• RPL and P2P-RPL Implementation, challenges and opportunities	2004–2015	–
H. Kharrufa et al. [30]	• RPL Review • Energy efficiency, QOS, Congestion, Mobility, and security.	• RPL application Domain • RPL challenges	2010–2017	• OF-based Energy efficiency and QOS
A. J. H. Witwit et al. [31]	• Traffic patterns • Energy efficiency • Reliability/ congestion • Mobility/ Security/Load Balancing	• RPL review • RPL Challenges	2013–2016	• RPL review
A. Sebastian et al. [32]	• Network efficiency • Load balancing parameters • Network stability	• Load Balancing	2013–2018	–
T. R. Bhattacharyya et al. [127]	• -	• Congestion and packet lost	2012–2018	–
H. lamaazi et al. (Our survey)	• Routing metrics • Objective function assessment/ enhancement • Single / Composite approach • Fuzzy logic/ Lexical/additive • Context awarnes, Multi path, other	• RPL-based Objective function	2013–2019	–

constrained nodes. This routing protocol supports different topologies such as single, point-to-point, multipoint-to-point and point-to-multipoint [12]. To build a route, RPL uses the Directed Acyclic Graphs (DAGs) concept where the nodes are organized as a tree structure called Destination-Oriented DAGs (DODAGs). In a DODAG, the sink nodes act as the root of the DAGs [12]. RPL uses four ICMPv6 control messages to maintain routing topology and update routing information. First, it uses the DODAG Information Object (DIO) to preserve the current rank of the node and calculate the distance between node and root used for selecting the preferred parent. Second, it transmits the Destination Advertisement Object (DAO) in upward traffic towards the selected parents. Third, it sends the DODAG Information Solicitation (DIS) to solicit DIO messages from a joinable node. And finally, the DAO-ACK message which represents an acknowledgement of the reception of DAO message is sent by DAO receiver [33].

Compared to the wired and ad hoc networks, low power and lossy networks present some particularities that characterize their behaviour. The main one is the use of RPL as the primary routing protocol for such networks. This protocol, thanks to its

Table 2
List of Abbreviations.

Symbol	Description
AMI	Advanced Metering Infrastructure
AVG_DEL	Average End-to-End Delay
CAFL	Fuzzy Logic based Clustering Algorithm
CHEF	Cluster Head Election mechanism using Fuzzy Logic
DIO:	DODAG Information Object
DAO:	Destination Advertissment Object
DIS:	DODAG Information Solicitation
DAG:	Directed Acyclic Graphs
DODAG:	Destination Oriented DAGs
ETX:	Expected Transmission Count
HC:	Hop Count
PC:	Power Consumption
EC	Energy Consumption
IPv6:	Internet Protocol version 6
IETF:	Internet Engineering Task Force
IoT:	Internet of Things
LQL	Link quality level
LoWPAN:	Low-Power Wireless Personal Area Networks
6LoWPAN:	IPv6 Low power Wireless Personal Area Networks
LLNs:	Low Power and Lossy Networks
LEACH	Low Energy Adaptive Clustering Hierarchy
MRHOF:	Minimum Hesterysis Objective Function
OF:	Objective Function
OF0:	Objective Function Zero
PDR:	Packet Delivery Ratio
PFI	Packet Forwarding Indication
PLR	Packet Loss Ratio
ROLL:	Routing Over Low power and Lossy networks
RPL:	Routing Protocol for Low Power and Lossy Networks
RX	Reception Ratio
RFC:	Requests for Comment
RSSI	Received Signal Strength Indicator
WSN:	Wireless Sensor Network

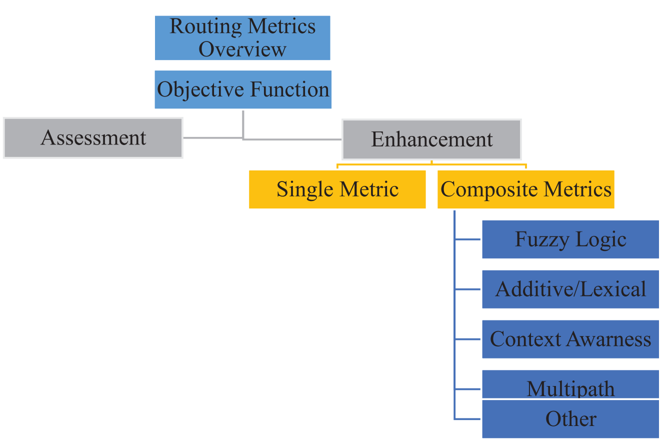


Fig. 1. Organization of the survey.

objective function, makes the adoption of the routing metrics very flexible [34]. The routing metrics are used to insure path cost evaluation, and to choose the shortest constrained path. Some implementations of RPL only require the use of a single metric while other ones need to define a set of routing metrics and constraints [35]. According to their characteristics, the routing metrics can be categorized as metrics related to the link or the node, metrics that present quality or quantity, and metrics that are static or dynamic. However, there is a difference between a routing metric and a routing constraint. Both of them may be used by the routing protocol as a criterium for selecting an optimal path. For example, a routing protocol can make use of a routing constraint to avoid unreliable links. In contrast, with a routing metric, the path is chosen based on the links that provide a defined level of reliability. The deployment of metrics or constraints depends on the RPL implantation needs.

Another characteristic that the routing metrics should consider is dynamicity. Indeed, the link or node metrics are not stable in the LLN networks and they change during the network operations. Let us consider, for example, the residual energy as a node metric for selecting a path. The nodes that operate in the network cannot preserve their energy all the time, which continuously reduces their residual energy. For this reason, the calculation of the path, based on this particular metric, changes according to the change and the dynamicity of these metrics [35]. Fig. 2 categorizes different routing metrics as follows.

Link metrics:

- √ *RSSI and LQI:* The physical layer allows specifying the network characteristics as the signal, frequency, voltage, etc. The main popular radio link estimators are the Received Signal Strength Indicator (RSSI) and the Link Quality Indicator (LQI). The RSSI is a hardware link layer, which acts as a radio transceiver loaded to verify the availability of the received frequency signal before sending data. Whereas, the LQI measures the reliability of the link using a range from 0 to 7 to indicate the quality level of link [36].
- √ *ETX:* The Expected Transmission Count is an indicator of network reliability. It presents the number of transmissions needed to receive an acknowledgement from the destination [37,38]. The path that provides the lowest value of ETX is chosen as the optimal way to reach the root. However, the high value of ETX reflects the unreliability of the network.

Node metrics:

- √ *Energy:* The energy is a node metric that presents the energy spent by nodes during their network operations. Because of the distribution of nodes and their distance to the sink,

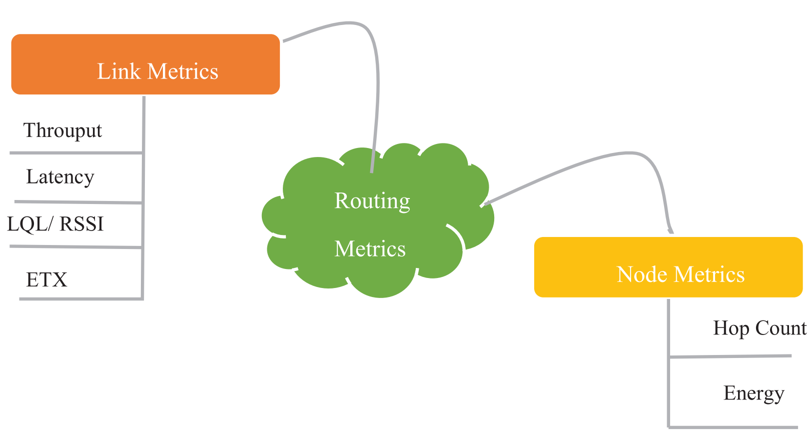


Fig. 2. Different node and link metrics used by the objective function.

some nodes may lose their energy faster. These bottlenecked nodes induce some failures and then decrease the network lifetime. For this reason, it is important to consider the residual energy of nodes when designing a new objective function [39].

√ *Hop Count:* The Hop-Count is the most routing metric used in wireless networks. It is used to measure the path length in a network. The main drawback of this metric is to choose the low path that provides low hop count whatsoever the link quality is [38,40].

√ *End-to-end Delay:* One of the important routing metrics needed for route building in RPL, is the delay. It presents the time required to transmit packets from sender nodes to the sink. This is a critical metric for real time applications. [41].

3. The objective function in RPL

The RPL constructs the DAG based on the objective function [42,43]. The path cost is calculated periodically according to a specific change in the network. The first one is when the selected metric is updated and the second one is when a new metric advertisement is received. The use of objective function by the routing protocol is based on three components:

1. The selected metric, which represents the metric that the node chooses to select the path.
2. The path cost, which measures the path property.
3. The best parent, which designates the parent that provides the highest path cost.

3.1. Standard OFs

3.1.1. Objective function zero (OF0)

The concept of the use of the objective function was realized in the first standardized objective function zero (OF0) [44]. By default, OF0 considers the hop count as a routing metric to select the best parents from candidate neighbours. During the DODAG construction, nodes should consider the shortest path in terms of hop count to the grounded root. The rank of this node should be closed to the root. To maintain the path diversity, the rank increase in a downward way from root to the candidate nodes. The OF0 was designed to be adequate with the low power and lossy network environments, but the use of node metric may provide poor link quality. Nodes select the path with the minimum hop count even if they are unreliable and lead to more retransmissions, which provides more packet loss. In addition, the choice of the same path that provides the shortest hop count allows having a more nodes failure, which affects the network lifetime.

3.1.2. Minimum rank hysteresis objective function (MRHOF)

The use of a static metric as an administrative cost to compute the best parent allows OF0 to consider the parent that provides fewer hops even if it may have poor connectivity. For this reason, the use of MRHOF (Minimum Rank with Hysteresis objective function) is based on a dynamic link metric such as expected transmission count (ETX) to recover rank stability. MRHOF was proposed by the IETF to resolve the static metric issues. It is designed to choose the path that provides the lowest path cost while avoiding churn overflow in the network. The MRHOF adopts two mechanisms to select the best path. First, it chooses the path with low rank. Second, it uses the hysteresis mechanism where the minimum rank is chosen only if it is less than the current path. The MRHOF supports the additive metrics. In the literature, two implementations of MRHOF are frequently defined, which we present in the following sections.

3.1.2.1. Minimum rank hysteresis objective function with ETX (ETXOF). By default, the MRHOF uses the expected transmission count (ETX) as a routing metric to select the best path [45]. The ETX presents the maximum number of retransmissions needed for a packet to be successfully received in the destination. The low value of the ETX means that the path is the best. The ETX is calculated from the sender nodes while the ETX of the sink one is equal to zero. The ETX is computed based on two main elements: the one hop ETX which, is related to the link estimator that defines the ETX of neighbours and the multi-hop ETX that covers the accumulative ETX of neighbours in the path between theme and the root. Thus, the cost of ETX presents the sum of both 1 hop ETX and multi-hop ETX. The optimal path is the one that provides the lower cost ETX. The ETX can be calculated according to the formula as follows [45]:

$$ETX = 1/Df * Dr$$

Where the Df is the forward delivery ratio that presents the probability for the successful incoming packets from source to destination and Dr is the reverse delivery ratio that presents the probability for the successful incoming acknowledgement from destination to source. The quality of a link in terms of reliability can be measured by the ETX value, low ETX cost indicates that the link in the network is more reliable [45].

3.1.2.2. Minimum rank hysteresis objective function with energy. Another implementation of MRHOF makes use of the energy as a criterion for selecting the best path. Nodes check the availability of a good link to the root periodically during network operation, which led nodes to consume more energy. To overcome this issue, MRHOF chooses the parent that remains high energy [45]. Compared to the MRHOF with ETX, MRHOF with energy can provides more packet loss and more delay. Table 3 compares the OF0 and MRHOF in terms of characteristics and composition.

4. Metrics composition approach

As explained in the previous section, routing metrics can be node or link metrics. These metrics can be used in the defined OF as single or combined metrics. In this section, we present the different methods of composition used in the literature [46].

4.1. Lexical metric composition

The lexical composition consists of comparing two routing metrics. The first composition metrics that provide low or high value according to the routing characteristic it will be selected as the best parent toward the root. In the case of equal values of the first component, the node will check the second component, which will determine the DODAG parent.

4.2. Additive metric composition

The additive approach is based on a defined OF that combines a set of metrics to provide one common metric in the output and then use the DIO messages to advertise this resulting metric. The routing metrics are aggregated throughout the path and involved in the DAG Metric Container Object. The additive composition use the following form

$$w = (a1 * HP) + (a2 * ETX)$$

where a1 and a2 values should satisfy these two conditions: 0<=a1, a2<=1 and a1+a2=1.

Fig. 3 shows how to compute the best parent according to both additive and lexical approach: the network is constituted

Table 3
Summary of different characteristics of both OF0 and MRHO.

	OF0 [44]		MRHOF [45]	
	Name	Description	Name	Description
Operations	**Computing Rank**	• The rank of a node is the sum of the rank of preferred parent and the rank increase variable that present the increase in the rank from parent to the node. (see RFC 6552).	**Computing the Path Cost**	• Is the cost of the path, based on link or node metrics, from a node to the root through a neighbor. It s calculated from the leaf neighbor. • By default node use the ETX metric else, if the selected metric is not available, the path cost is set to MAX_PATH_COST
	Parent Selection	The parent's selection rules are applied to: • A node that increases its rank • A router with satisfying connectivity and suitability implementation • A router with higher order interface • A router that provides connectivity to a set of desirable root • A router that provides connectivity to a grounded DODAG. • A router that provides connectivity to the most recent DODAG from two candidate parents. • The node providing lower resulting rank. • DODAG version that has an alternate parent • Already used preferred parent • A router that sent a DIO message recently.	**Parent Selection**	• Based on the path cost, the node selects the preferred parents from candidates ones.
			Computing Rank	• The path cost is converted into a rank value • If the rank is undefined, nodes choose the rank of the leaf neighbor.
			Advertising the Path Cost	• When the node selects its preferred parent, it sets the cur_min_path_cost e variable to the path cost. The node advertises the highest cost that will be carried in the metric container.
			Working without Metric Containers	• If there is no metric container, by default MRHOF uses the ETX metric and add it to the advertised rank to determine the rank of paths.
Operands	**Variables**	• Step_of_rank • Rank_increase	**Variables**	• cur_min_path_cost
	Parameters	• Stretch_of_rank • Rank_factor	**Parameters**	• -MAX_LINK_METRIC • -MAX_PATH_COST • -PARENT_SWITCH_THRESHOLD • -PARENT_SET_SIZE • -ALLOW_FLOATING_ROOT
	Constants	• DEFAULT_STEP_OF_RANK: 3 • MINIMUM_STEP_OF_RANK: 1 • MAXIMUM_STEP_OF_RANK: 9 • DEFAULT_RANK_STRETCH: 0 • MAXIMUM_RANK_STRETCH: 5 • DEFAULT_RANK_FACTOR: 1 • MINIMUM_RANK_FACTOR: 1 • MAXIMUM_RANK_FACTOR: 4		

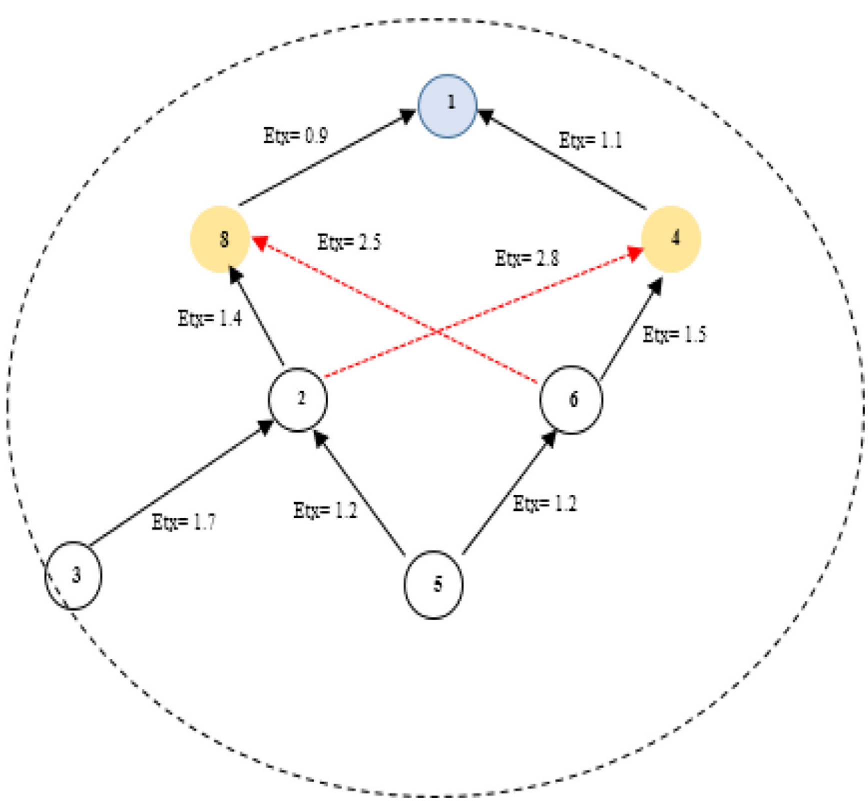


Fig. 3. Parent selection process based on lexical and additive combinations.

Table 4
Requirements for good routing metrics composition.

	Metrics requirements	Description
	Be well-defined	An efficient composite metric should based on well-defined metrics and avoid.
	Reflect the basic characteristics of LLNs	Metrics should consider the nodes constraints as preserving energy, load balancing and link stability.
	Be orthogonal and not antagonistic.	The chosen metrics should'nt neither refelect the same LLNs caracteristics and one don't eliminate the impact of the other.
	Exhibit continuity.	Small change in metric values should'nt provides an instabilities or inconsistencies.
	Be scalable.	The composite metrics should be able to adapt with the network scalability.
Routing composition	Have known and identified sources of inaccuracies and measurement uncertainties.	The sources of inaccuracies of the chosen metrics, must be identified.
	Follow the same properties and rules.	The chosen metrics with different properties must be transformed to have the same properties.
	Not lead to routing inconsistencies.	The dynamic metrics can provides routing instability which require the use of hysteresis factor to reduce these alterations
	Hold properties of isotonicity and monotonicity.	The routing metrics should be monotonic and isotonic to satisfy the routing requirements of convergence, efficiency and loop-avoiding.
	Be normalized	To provide a good QOS caracteristic, the composite mtrics should apply the normalized process.

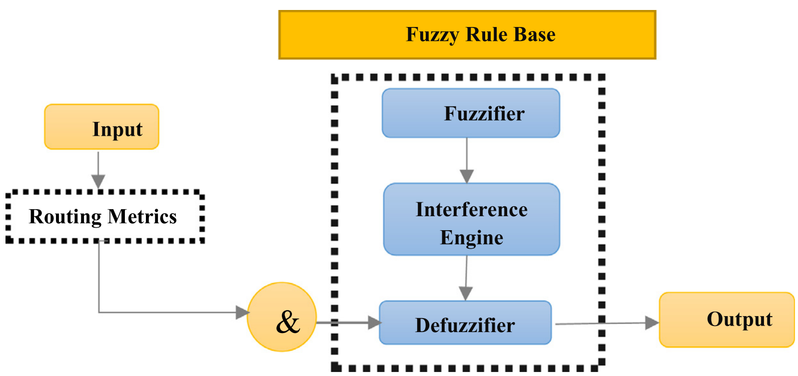


Fig. 4. The process of Fuzzy Interference System (FIS) applied to the output metric.

by 7 nodes where the blue node is the sink, the yellow nodes are the nearest parents to the root and white ones represent the child.

Table 4 describes the different requirements of a good routing metric composition.

4.3. Fuzzy logic composition

The fuzzy logic approach is widely used in the literature to combine a set of information with different characteristics [47]. Based on the concept of membership, fuzzy logic converts a several input variables into one common output. Fuzzy logic adopts the use of linguistic variables to classify data and then to calculate the degree of dependency between these variables. To apply the fuzzy process model, a set of steps should be followed as described in Fig. 4.

(i) Fuzzification: takes a predetermined input variable and specify its membership degree (fuzziness) for fuzzy sets [48].
(ii) Fuzzy inference: allows combining fuzzified inputs and then calculating the output [48].
(iii) Aggregation: unifies the outputs if they depend on more than one rule [48].
(iv) Defuzzification: transforms the fuzzy output into a determined value [48].

4.3.1. Example of the fuzzy logic application

To illustrate the fuzzy logic composition, we consider two routing metrics, ETX and HC. These metrics are represented as a linguistic variable:

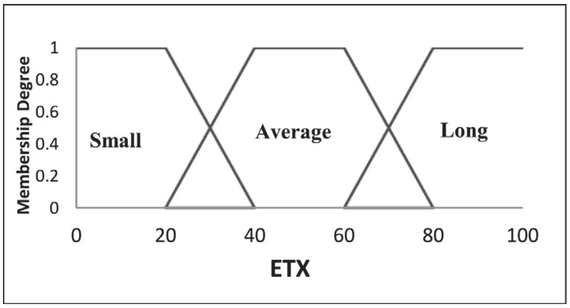
- ETX: number of expected transmissions count needed for a packet to successfully reach the destination.
- HC: is a node metric that determines the path with a low number of hops to the destination.

The fuzzy logic uses the linguistic variable to determine the degree of dependency between the routing metrics to provide a common output metric [49]. In our example, the linguistic variables used to represent the ETX (input) are short, average and long while for HC, they are defined as follows: near, medium and far. Fig. 5 shows the membership between these linguistic variables. Higher value of both ETX and HC represent the worst path to the destination, while small values determine the good route.

From these membership functions, five values of quality are provided: very-bad, bad, average, good and very-good. These values are defuzzified and transformed on one common output. The selection of the path considers only the two qualities “very good” and “good”.

5. OF emerging research directions

In this section, we survey the RPL based objective function assessment and enhancements. We provide a thorough analysis



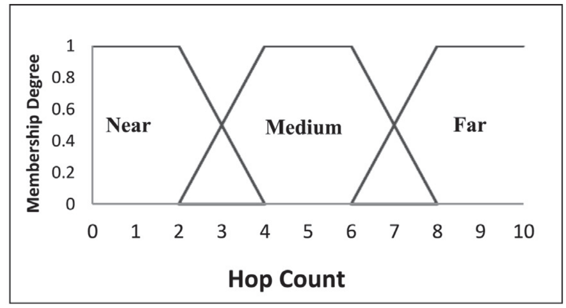


Fig. 5. Membership functions for both ETX and HC.

of the proposed evaluation scenarios and enhancement and we underline their shortcoming. The enhancement part includes the implementation of single and composite metrics. The composite metrics are organized according to the adopted approach including Fuzzy logic, lexical/additive, context Awareness [50] and Multi-path. The Tables 6–11, summarize the studied OFs including their characteristics, methods, and improvement/weakness. Moreover, we propose a statistical analysis of the different studies of both OFs assessment and enhancement.

5.1. RPL based OFs assessment

In [51], the authors propose an assessment of RPL performances based on the Objective Function. They use the default objective function MRHOF and the Objective Function Zero (OF0) in order to distinguish which Objective Function provides better performances for RPL. The simulation environment uses various radio models (Unit Disc Graph Model—Distance Loss, Unit Disc Graph Model-Constant Loss, Multi-Path Ray-Tracer Medium) and scaled network. To make a comparison between the two objective functions, a set of metrics are calculated: Packet Delivery Ratio, Control Traffic Overhead, Power Consumption (PC), and Network ETX. As a result, the objective function based on ETX metrics (MRHOF) provides better performances in all scenarios compared to the objective function based on a hop count metric (OF0).

Authors in [52] propose an assessment of the standardized objective functions namely MRHOF and OF0. They focus on different parameters such as convergence time, average PC, average ETX, average hop, Packet Delivery Ratio (PDR), and the average latency. In the implementation process, the authors adopted different scenarios based on different topologies, different reception ratio (RX) and various amount of transmitted packets. In addition, the assessment was tested in both static and mobile environment. The results show that MRHOF is adequate for reliable networks while OF0 is suitable for a network that needs fast convergence and low power consumption. Moreover, OF0 acts better in the mobile environment than MRHOF.

Another assessment of the standardized OF is investigated in [53]. The authors adopt two different topologies including random and grid, in addition to the different transmission rate. They study the impact of these parameters on the RPL performances and compare the use of MRHOF and OF0. The results show that with an RX of 60%, both OFs act better than the use of the RX equal to 100% in terms of PDR and PC independently of the distribution (grid or random). Furthermore, the use of a low density of 30–40 nodes incite the MRHOF to provides better RPL performances than OF0. Similarly, authors in [54] adopt grid and random topologies and an RX of 60% to assess RPL behaviour using both MRHOF and OF0. The results show that with a fixed value of RX equal to 60% and with a density of 50–65, both OFs act similarly and provide best performances in terms of PDR and PC. Compared to OF0, MRHOF provides better PDR and PC performances.

Authors in [55] focused on the performance analysis of RPL based on its standardized OFs. They compare the impact of the use of MRHOF based ETX, MRHOF based energy and the OF0. The proposed study involved two steps. The first step focuses on checking the impact of the traffic load by varying the inter-packet transmission from 1to 6 min according to the AMI context. The second step is based on the number of nodes in the network and maintaining the transmitting packet of 1 packet per 4 min. The simulation results show that both OF0 and MRHOF based ETX are negatively impacted by the high load. In addition, MRHOF based Energy provides bad performances in terms of PDR and delay. Moreover, the MRHOF based ETX degrades the network performances especially in terms of PDR when the number of nodes increases. At least, MRHOF based ETX and OF0 keeps similar end-to-end delay close to 4 s.

Another investigation of OFs is proposed in [56]. The authors compare the MRHOF based ETX with the OF0. They are based on the network scalability with a random distribution. For simulation metrics, they choose the packet lost ratio (PLR), latency and PC. As results MRHOF based ETX provides the best performances of the network in terms of PLR and Latency while the OF0 consumes less PC. In addition, the OF0 is not affected by the network size. The authors in [57] have another vision of OFs evaluation. They focused on the use of multi-sink in the network in order to extrapolate its impact of the routing performances. The authors use a random distribution with a different number of sink nodes of 1, 5 and 10 nodes. They found that the deployment of the multi sink strongly affects network performances positively. Furthermore, the OF based ETX provides better results in terms of PDR, Throughput and Energy consumption than Of based Hop Count does.

The authors in [58] use a variety of parameters and environments to assess the standardized OFs. They use stationary nodes in the grid distribution while the mobile nodes are distributed in a random way. For the simulation process, three densities of 26, 50, and 82 are considered in addition to the three transmission ranges of 11, 20, and 50 m. A set of metrics are taking into consideration including convergence time, changes in DoDAG tree structures, average churn in the network, Average Power Consumption, Average Listen Duty Cycle, Average Transmit Duty Cycle, Average received packets, average lost packets, average duplicate packets, and average hop count. The results show that OF0 outperforms MRHOF in terms of energy, convergence time and duty cycles in static-grid distribution. Otherwise, both OFs acts similarly in mobile-random distribution except PC where OF0 consumes less power.

To respond to the Wireless Sensor Networks (WSNs) requirements on saving energy and self-adapting with non-trusted nodes, authors in [59] study a routing metric called TXPFI which present the expected number of frame transmissions needed for successful sending data. This metric can be applied in a network where a set of malicious and non-cooperative nodes are present. The authors present a model that uses legitimate and malicious traffic forwarders. A comparison has been made between the lexical and additive combination of routing metrics including Hop count, ETX and packet forwarding indication (PFI). The results show that the use of TXPFI in RPL is more efficient than other composite metrics in terms of mitigation of attacks and avoiding unreliable links. TXPFI reduce the packet drop rate and significantly improve the network performances compared to composite metrics. TXPFI allows a quick converging network with less generated control messages, which allows it to be adequate for a constrained network that needs energy-efficient routing.

Authors in [43] propose an assessment of the standard objective functions namely MRHOF and OF0. They studied three scenarios: network density, type of mobility models and node distributions. Based on a set of metrics, the simulation results show that in a static environment, MRHOF provides the best performances with the scalability of the network while with mobile environment OF0 shows better results. For different node distributions including random, grid and manual distributions, both objective functions provide similar results for all metrics except for a linear position where MRHOF consumes more energy and provide higher control traffic overhead.

To highlight the importance of the rank security in the parent selection, authors in [60] propose an assessment of the objective function vulnerabilities. The proposed study shows that the rank attack can prevent a particular node to participate in the DODAG building or to reach the destination. The results of this assessment demonstrate that compared to OF0, the MRHOF is more vulnerable to the rank attack. Moreover, MRHOF increases the APC in the malicious scenario by up 0.01% compared to OF0. These results show the importance of the vulnerability of the rank computation when designing a new objective function.

Another assessment of the standard objective functions is presented in [61]. The authors propose two different scenarios based on the variation of the sending interval and the network densities. The results show a clear impact of the sending interval variation on the network performances. The paper focuses on the parameters variation and their impact on the routing behaviour without concluding on the best standard OFs in such conditions. Table 5 provides a summary of different studies related to RPL assessment.

5.2. Statistics, analysis, and discussion for OFs assessment

In this subsection, we provide a statistical analysis of the research papers that have studied RPL so far, based on the evaluation methods.

5.2.1. By the number of nodes

Fig. 6 shows the distribution of the number of nodes and their frequencies used for in simulation assessment. The density of the network is a major and critical parameter in assessment studies. In a large platform, the simulation is conducted with a number of 75∼200 nodes while it is 35∼65 for a medium density and 10∼30 for a low density. The majority of previous studies used 20 and 40 nodes with 14% and 12% respectively followed by 30 with 10% and 25, and 100 by 7%. It is worth noting that the density of networks is not only related to the number of nodes, but also to the interference range. For instance, for 30 nodes in an interference range of 25 m, the network is considered dense, whereas for 50 m or 100 m with the same interference range, it is considered sparse.

5.2.2. By routing metrics

Fig. 7 shows the distribution of the most used metrics in RPL simulation assessment studies. The energy consumption is the most critical challenge for devices running the RPL protocol. For this reason, many research papers focus on evaluating the impact of the objective function on energy consumption. We can notice that 27% of the surveyed papers use the energy consumption as a parameter of evaluating the proposed scenarios followed by PDR with 16%, ETX with 11% and Hop Count and throughput with 8%. For other metrics, they are employed equitably with a count of 5% respectively for PLR, Packet Received, Packet Loss, latency and, convergence time. This can be explained by the fact that all surveyed papers use exclusively the Cooja simulator for objective function assessment. Indeed, Cooja provides most of the features that compute the power consumption such as CollectView, PowerTrace, and PowerTracker. In addition, Cooja provides a TimeLine module that allows visualizing both network traffic and power consumption of the sensor network. Furthermore, it is worth noting that other metrics exist that are not widely used in the objective function assessment studies (Fig. 8) such as, malicious nodes, Duplicate packet, Churn, Probability of forwarding, Duty Cycle, Frame Count and number of transmissions.

5.2.3. By topologies and environments

The topology of the network has a critical impact on routing performances. For this reason, each surveyed paper considers carefully the use of adequate distribution of nodes according to the proposed scenarios. As shown in Fig. 9, the most used topologies are the random (56%) compared to the grid (33%), Ellipse (5%), and Manual (6%). In the real world, the sensors are generally distributed randomly to collect information, which explains the use of random topology in simulation studies to reflect the real distribution of sensors. We notice that only a few (21%) mobility-related works have studied OFs assessments, whereas 79% in static environments. Again, this conclusion invites the RPL research community to investigate more the mobile context.

5.3. Recent enhancements of the OF based RPL

5.3.1. Single metrics

In [14], the authors propose a new objective function (OF) based on a single metric: the remaining energy. In contrast to the traditional objective function that uses link metrics as a single criterion (eg. 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 equalizes 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 a single metric still not efficient since it does not consider the link quality of the network. Similarly, Authors in [62] propose a new objective function based on energy efficiency. They study the impact of the new proposal on the WSN network using a real deployment of two different scenarios. They consider only the real-time and battery charge requirements of the WSN network as monitoring or surveillance uses. Compared to the OF based ETX and OF based hop count, OF-Energy allows keeping nodes running for a long time which extends network lifetime, while it reduces the packet loss and delay. Using energy as a single metric to improve the routing protocol may degrade others parameters especially those related to the link quality which is not discussed in the paper. However, the proposal is compared only against the standard OFs.

Another study of RPL has been made in the context of smart grid communication running on Advanced Metering Infrastructure (AMI) networks [63]. The authors used a new Objective Function based on the Hop Count routing metric to select the preferred parents. The OF0 is compared to the existing objective functions that use Expected Transmission Count. This optimization offers better performances in terms of end-to-end delay and packet delivery ratio (PDR). However, the proposed solution is tested in terms of PDR and delay, which neglects other critical metrics such as network lifetime, convergence, and the number of preferred parents.

Table 5
Objective Functions-related assessment research.

OF	Number of nodes	Topology	Environment	Other scenario	Measured metrics	Results	Publication	Year
MRHOF and OF0 [51]	1 sink 40, 80, 100 and 200 senders	Random	Static	-UDGM—Distance Loss, -UDGM-Constant Loss, -Multi-Path -RTM	PDR, Overhead, PC, and ETX	MRHOF provide better performances in all scenarios	Journal	2015
MRHOF and OF0 [52]	25, 49, 81	Random grid	Static, mobile	-RX= 25%, 50%, 75%, 100% -Data Rate = 10, 30, 50, 70 packet/min	-Convergence time -PC -ETX -Hop Count	MRHOF is more reliable OF0 provides faster convergence time and consume less power	Conference	2016
MRHOF and OF0 [53]	20, 30, 40, 45	Random grid	Static,	-RX= 20%, 60%, 100%	-PDR -PC	Both OFs acts better with an RX= 60% MRHOF acts better with low density than OF0	Conference	2015
MRHOF and OF0 [54]	50, 65, 75, 85	Random grid	Static,	RX=60%	-PDR -PC	Both OFs acts better with an RX= 60% MRHOF acts better with low density than OF0	Journal	2016
MRHOF_ ETX MRHOF_Energy and OF0 [55]	20, 40, 60, 80, 100, 120, 140	Random	Static	Throughput 1packet/4min	-Latency -PDR -Overhead -Throughput	-OF0 acts better in high density -MRHOF_Energy provides poor performances -MRHOF_ETX doesn't support scalability in terms of PDR -both OFs maintain the same end-to-end delay.	Conference	2017
MRHOF_ETX OF0 [56]	11, 16, 21, 26, 31, 36, 41, 46	Random	static	Transmitted packet 1 packet/min	-Latency -PLR -PC	MRHOF_ETX provides best PLR and latency OF0 consumes less power and not affected by the network size	Conference	2017
ETX and HC [57]	Sink = 1, 5, 10 Sender= 35	Random	Static	Multi-sink	-Lost packet, PDR -Enegy Consumption -Throughput -Received packet	The Multi-sinks impact the network performances ETX is better than HC in terms of PDR, Throughput and energy consumption	Conference	2017
MRHOF, OF0 [58]	1 sink 25, 49, 81 senders	Random grid	Static Mobile	TR= 11 m, 20 m, 50m RX= 25%, 50%, 75%, 100%	-Convergence time -Churn, Duty cycle -PC -Received, lost, duplicated packets, Hop count	OF0 is better than MRHOF in terms of PC, convergence time and duty cycle In a mobile OF0 consumes less power	JOURNAL	2017
ETX, HC, PFI, TXPFI [59]	100	Grid	Static	Nodes with 1, 5, 8 neighbours	-malicious nodes -Frame count -forwarding Probability -ETX, PLR	TXPFI is more efficient in terms of mitigation of attacks and avoiding unreliable links. - reduce the packet drop rate and control messages. -increase convergence	Symposium	2014
MRHOF and OF0 [43]	10, 20, 30	Random Grid Linear And manual	Static mobile	–	-ETX, -Hop Count, -lost packets, -Energy Consumption -Overhead	-MRHOF acts better in static -OF0 acts better with mobility -Similar results for all distributions except linear	Conference	2016
MRHOF, OF0 [60]	1 sink 19 senders 1 malicious node	Random	Static	Non-malicious node Malicious node	-Throughput, -APC	Increases APC when using malicious nodes	Conference	2018
MRHOF, OF0 [61]	20, 30, 40	Random	Static	Different TX values Different sending intervals	-PDR -PC	Increases PDR Decreases in PC	Symposium	2018

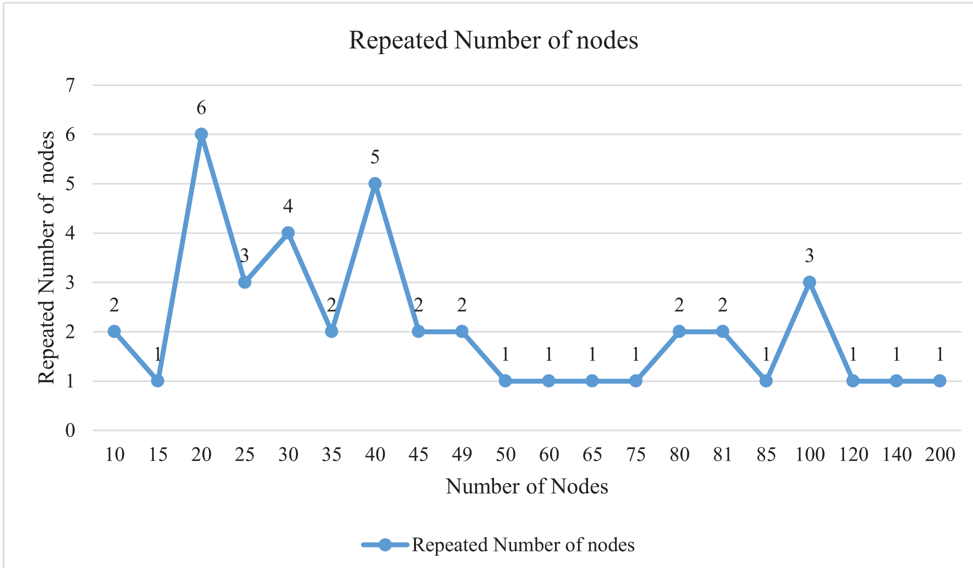
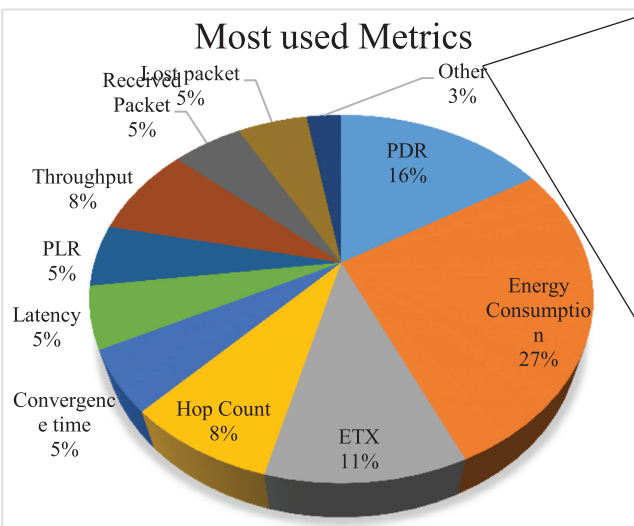


Fig. 6. Statistical illustration of the number of nodes used for assessment studies.



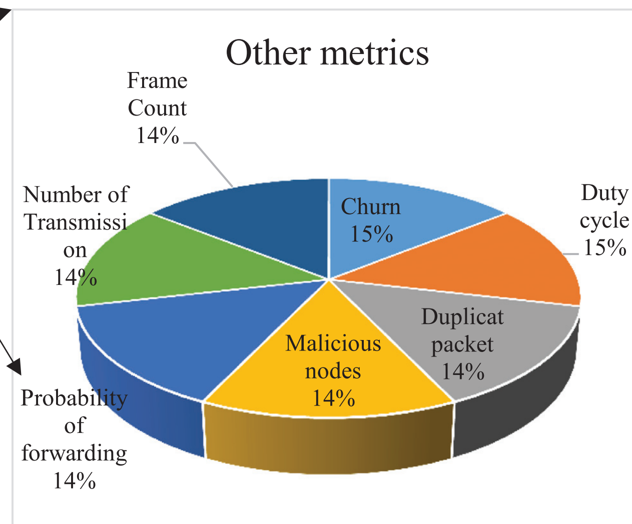


Fig. 7. Distribution of the most metrics used for assessment studies. **Fig. 8.** Metrics lowly used for assessment studies.

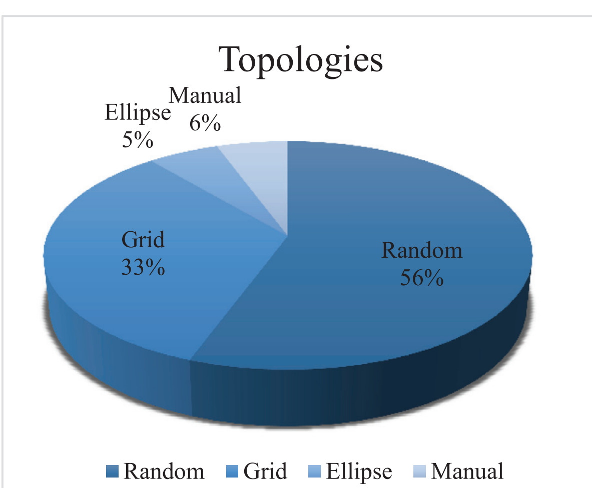


Fig. 9. Distribution of the topologies used for assessments.

To extrapolate the impact of the IPv6 packet length in network layer and the number of fragments in the MAC layer, the authors in [64] investigate the 6LoWPAN performances using a variety of received signal strength indicator (RSSI) and payload measurements. Based on experimental results, the authors propose a new A RSSI-based IPv6 routing metrics for RPL. This new routing metrics allows improving transmission quality for 6LoWPAN performance in terms of throughput, delay, and packet size. It allows increasing the IPv6/UDP packet reception rate. To solve the problem of the long delay provided by nodes that spend more time to receive an acknowledgement, authors in [65] propose a new metric called AVG_DEL. This metric allows minimizing the delay of a node in the DODAG running with the very low duty cycles. The authors propose a set of change in the ContikiMAC radio duty cycle to regulate the wake-up and the sleeping time of nodes. Compared to ETX metric, AVG_DEL decrease considerably the end-to-end delay. In this solution, only the number of packets and the end-to-end delay are considered while other efficient metrics are neglected as overhead, energy, PDR. Moreover, the proposed metric is combined only to the standard metric. To achieve network reliability, the authors in [66] propose a new mechanism that resolves the problem of packet loss in downward routing. They classify the causes of packet loss in three categories: the MAC-layer drop, routing inconsistency, and the IEEE 802.15.4 1-byte sequence number. To overcome these issues, the authors define a variant of ETX that balances reliability and path length. Then, they improve node behaviuor according to the context awareness in order to optimally choose the best link toward the destination. Also, they added a routing state for packet forward and maintenance. These solutions allow reducing the loss rates by up 0.1%. However, the mechanism increases the overhead by up 27%. The proposed approach was tested in downward traffic, which is more beneficial for the case of low traffic.

To improve the quality of services provided by RPL, authors in [67] propose a new objective function based on connection status called Best-Friend ETX (BF-ETX). This metric allows updating the ETX when the objective function operates for nodes that are not backed up. The new BF-ETX improves network performances in terms of power consumption and network latency. However, this solution neglects some important parameters such as the convergence time and the parent changes that can result from the ETX updates. The proposed enhancement using single metrics are summarized in Table 6 as follow.

5.3.2. Composite metrics

There are many research studies that have been interested in improving the RPL routing protocol, using a set of methods such as fuzzy logic in order to optimize the objective function [41,68]. This optimization can use single or multiple metrics in order to make the choice of the route based on the best decision. The choice of the optimal objective function is handled by the user with respects to the application requirements. According to a set of studies, the use of single metrics leads to some limitations. For instance, an objective function that requires good reliability chooses the parent that provides low ETX. In contrast, the use of low ETX for parent selection may push nodes to consume more energy.

5.3.2.1. Objective function based on fuzzy logic method. To respond to the requirements of constrained applications that use RPL, authors in [68] 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, namely the Expected Transmission Count, the 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 increases when the network experiences heavy data traffic. This proposal is compared only against the standard MRHOF that uses a single metric. The proposed solution was not compared to other approaches that use a combination or multiple metrics, which limits its efficiency.

In [41], the authors designed a new Objective Function (OF-FL) that combines several metrics based on fuzzy logic methods. This method uses a set of fuzzy parameters considered for the configuration of a routing decision. In comparison to 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. Authors in [69], focus on the mobility requirement as the main challenge of IoT application. They supposed to optimize the RPL objective function by proposing a new OF called FMOF based on combining parameters, which are ETX, Hop Count and the Received Signal Strength Indicator (RSSI) and using fuzzy logic model. The fuzzy decision was applied to the hand-off enabled RPL mechanism. The authors were defined and extensive simulation where they test different weighting scenarios to specify the adequate scenario that guarantees reliability. As results, the FMOF acts better in terms of delivering data from Mobile Nodes to the sink and allows routes to be updated more frequently. In addition, FMOF has the best-provided PDR and hand-off delay than OF0 and MRHOF. This new proposal is compared only to the standard OFs, which reduce its efficiency, faced another candidate proposal.

Another solution for networks routing is the clustering approach [70,71]. In [72], the authors use the fuzzy logic method for Cluster Head selection. The main process of this proposal is to apply the fuzzy logic method to select a cluster head after the division of cluster into sub-clusters. The comparison has been made with LEACH and CHEF approaches [73,74]. Simulation results show that the proposed method improves the performances in terms of lifetime and energy consumption. It allows reducing the energy consumption and maximizing 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. This allows for suspending information continuity. To maximize the network lifetime and minimize the energy consumption, authors in [75] propose a new clustering approach called a Fuzzy Logic based Clustering Algorithm for WSN (CAFL) to overcome the WSN requirement. The proposed solution is based on both cluster heads (CHs) selection and cluster formation. During the CHs selection process, the fuzzy parameters chosen as in input for the Fuzzification process are the residual energy and the node rank (distance to the sink). For the cluster formation, the fuzzy inputs are the residual energy of CH and the distance to the CHs. Compared to the Low Energy Adaptive Clustering Hierarchy (LEACH) [74], CHEF and LEACH-ERE, the CAFL outperforms this routing protocol in terms of network lifetime, stability and received packets.

The authors in [76] propose an improvement of RPL by considering quality of services requirements. To this end they define a new objective function based on a Multi fuzzy logic model (ML-FL). The model considers three categories of metrics namely node, channel and link metrics. For node metrics, the metrics are energy, ETX, and neighbours in connectivity while for the channel metrics the metrics used are the capacity, RSRQ and the bandwidth, whereas the link metrics are link stability, hop count and the mobility. In addition, the authors propose another RPL enhancement that considers the multicast forwarding algorithm which is Enhanced Bidirectional Multicast RPL Forwarding. This new algorithm allows solving the problem of duplicated packets. As a result, the proposed unicast and multicast algorithm shows better performances than the previous algorithms in RPL in terms of delay, PDR, energy and hop count. The proposed ML-FL was compared to the OF-FL an objective function based combined metrics and that use the fuzzy logic, but the two OFs are tested in a different environment (ML-FL in OMNET++ and OF-FL and OF0 in Contiki) which makes its efficiency not convenient.

The authors in [77] propose a solution to reduce the energy consumption of the sensors based on the mobile station. They propose to adopt the clustering approach realized by the fuzzy method. The fuzzy controller monitors the mobile base station that moves to the cluster head according to the level of priority. The Simulation results show an increase in terms of the network lifetime. However, this implementation considers only the network lifetime as the main metric for performance evaluation with no interest to the other metrics such as the overhead or the PDR.

Another proposal of composite metrics using fuzzy logic method is presented in [39]. The authors highlight the single metric limitations. They combine the ETX metric and the total energy

Table 6
Objective Functions-related research based on single metrics.

OFs	Metrics	Method	Topology	Improvement	Shortcoming	Experiment	Simulation	Simulator	Year	Publication
OF-Energy [14]	Remaining Energy	–		Equalizing the distribution of energy	More lost packet	No	Yes	Contiki OS Cooja	2013	Research repport
OF-ENERGY [62]	Hop Count, ETX, Remaining energy	Basic and extended WSN deployment	Star and three	Extend network lifetime, reduces the packet loss and delay	Compared to the standard OF based EXT	Yes	No	Contiki OS	2015	Forum
OF0 [63]	Hop count	Smart grid communication running on AMI		Better end-to-end delay and packet delivery ratio (PDR).	Compared it to the standard OF based ETX	No	Yes	Contiki OS Cooja	2014	Journal
AVG_DEL [65]	delay	Implementation of AVG-DEL Duty cycle regulation	Manual	Decrease considerably the end-to-end delay	Compared only to the standard ETX	no	yes	contiki	2013	Conference
RSSI-based IPv6 [64]	RSSI	fragmentation	–	High transmission/ reception packet rate	Not compared to any candidate solution	yes	no	Contiki, Zigduino devices, AT-mega128RFA1 microcontroller	2014	Conference
Five-Nines [66]	ETX	Variation of the ETX Context awarnes for parent selection Routing state	Random	More reliability Reduce packet loss	Extra traffic	yes	No	Contiki, IoT-LAB testbed in	2017	Journal
BF-ETX [67]	ETX	ETX update that considers connection status	Random	Reduce PC Improve latency	Few network parameters	No	Yes	Contiki, Cooja Simulator	2018	Transaction

consumption, which represents the energy spent by nodes among the path from nodes to the root. Using the hop count as a metric for nodes redirection, they present a new objective function called OF-EC. OF-EC shows its effectiveness in terms of PDR, network lifetime, convergence time, latency, overhead, and energy consumption compared to candidate approach namely OF-FUZZY, MRHOF and ENTOT. Similarly, authors in [80] propose to combine ETX, Hop Count and Consumed Energy using fuzzy logic providing a new objective function (DQCA-OFs). Four objective functions are developed depending on the context aware (reliability, delay, lifetime or quality of services (QOS)). The proposed DQCA-OF guaranties high reliability reaching approximately 100% of delivered packets. In addition, it allows reducing the end-to-end delay and improving the QOS, which positively affects the network lifetime that is improved by up 30%. The efficiency of DQCA-OF was tested by considering a density of 20 nodes, which needs more tests for a large network. To guaranty link reliability and to reduce congestion, authors in [78] propose a new Composite Metric Objective Function (CMOF) that combines both latency and ETX metrics using the fuzzy logic method. The authors are motivated by the fact that the existing OFs do not satisfy the latency and PDR requirements, especially for real-time applications. Thus, the combined latency across protocol layers is based on two main parameters; queue delays and channel access delay. Furthermore, the authors use a power control mechanism to detect and avoid contention. CMOF outperforms MRHOF in terms of PDR and latency due to the use of latency as criteria for parent selection. However, this approach was evaluated using a very low density of network, which is not sufficient to prove the CMOF efficiency. To ensure energy aware efficiency, the authors in [79] propose fuzzy logic based on energy aware routing protocol (FLEARPL) that combines ETX, load and residual energy (RER) routing metrics. These metrics are used to calculate the node rank in order to select the best parent. The simulation results demonstrate that with FLEA-RPL, the PDR is improved by up 2–5%, which leads to an increase of network lifetime by up 10–12%. However, the study lakes results related to the overhead and to load balancing. Table 7 provides a summary of the different studies using fuzzy logic approach:

5.3.2.2. Objective function based on context awareness. In [81], the authors proposed an optimized objective function of RPL that considers a context-awareness [82]. The developed OF is 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 OF 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.

In [83], the authors propose a new Objective Function based on Scalable Context-Aware called SCAOF. This OF can adapt RPL to the environmental monitoring of Agricultural Low-power and Lossy Networks (A-LLNs). This adaptation is based on a combination of energy-aware, reliability-aware, robustness-aware and resource-aware according to the composite routing metrics approach. Performance evaluation of the proposed RPAL was verified on both simulation and field tests. Simulation results prove that in different simulation scenarios and hardware testbed, SCAOF can deliver the desired advantages on network lifetime extension, and high efficiency and reliability.

To address the congestion problem, authors in [84] propose a new objective function called Congestion-Aware Objective Function (CA-OF). Based on a previous study [85], the authors conclude that the buffer overflow leads to more packet loss in a heavy network. For this reason, they have used the buffer occupancy as a routing metric in conjunction with ETX. This combination compared to the OF based on ETX, OF based on hop count and OF based on Energy, the CA-OF provides high PDR and Throughput while it reduces the energy consumption. However, the proposed CA-OF was compared only with the standard OFs. The surveyed studies related to RPL enhancement using context Awarness are summarized in Table 8.

5.3.2.3. Objective function based on lexical or additive method. In order to equalize the distribution of energy among nodes with an extension of network lifetime, authors in [86] propose two objective functions named respectively Parent Energy Objective Function (PEOF) and (PEOF2) which consider both ETX and remaining energy as routing metrics to select the best parent. PEOF considers one hop and then selects the parent based on remaining energy and ETX while PEOF2 uses the remaining energy of all parents at each hop along the path. The simulation is evaluated with the symmetric and asymmetric dense network. The simulation results show that PEOF2 provide 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.

Another enhancement of the objective function using a combination of routing metrics is presented in [87]. Authors propose to combine hop count (HC), Remaining Energy (ENG), Expected Transmission Count (ETX) and Packet Forward Indicator (PFI). The results reveal that the combination of ENG and HC reduce the PC with no impact on the latency and packet loss. Additionally, authors conclude that the HC is necessary for any combination in order to conduct packet 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 is no packet lost. In this case, when a node is lost it cannot be detected if only there is no retransmission from the parent node. At least the ENG used only not consider the destination when nodes built the route. Brief, ENG or PFI minimize the performance, but not consider the route to the DODAG root.

Similarly, the authors of [88] suggested a new optimization of the Minimum Rank Hysterisis Objective Function (MRHOF) named PER-HOP ETX. It can resolve the problem of a long single hop caused by both the MRHOF and OF0 (Objective Function zero) when the network is dense. This proposed amelioration provides better parameters compared to the OF0 and MRHOF in terms of energy consumption, latency and packet delivery ratio. However, PER-HOP ETX can consume more energy in a small network, which means that this solution is not suitable for networks presenting low nodes density.

Authors in [89] propose a new objective function called EEQ. It is an additive combination of three metrics namely ETX, Energy Consumption, and Queue length. The main goal of this OF is to keep nearly bottlenecked nodes running on the network to directly send data to the destination. Evaluated on the high and low density of the network, EEQ reduces the overhead compared to the standard MRHOF and OF0. However, using a single parameter (intensity traffic loads) to assess the extensive objective function is not sufficient. Indeed, though these parameters are improved but they cannot justify the absence of the other parameters such as the energy consumption, lifetime and the network convergence.

To improve the end to end delay (EED), authors in [90] make a set of modification to RPL implementation. They propose an End-to-End Delay Estimation Mechanism (EEDEM) used for delay

Table 7
Objective Functions-related research based on composite metrics using a fuzzy logic approach.

OFs	Metrics	topology	Improvement	Shortcoming	Experiment	Simulation	Simulator	Year	Publication
OF-FUZZY [68]	ETX, Delay, Remaining Energy	Random	Best PDR and delay equalize energy distribution	Compared only to MRHOF	Yes	No	Real indoor WSN Contiki OS	2015	Other (archive)
OF-FL [41]	Delay, hop count, ETX and LQL	Random	Low delay Low packet lost in high density Equalize energy distribution	Compared only to MRHOF and OF0	No	Yes	Cooja Contiki OS	2015	Journal
FMOF [69]	ETX, Hop Count and the Received Signal Strength Indicator (RSSI)	Linear	High sent packets Routes are updated frequently. Provides best PDR and hand-off delay	Compared only to MRHOF and OF0	No	Yes	Cooja Contiki OS	2017	Conference
LEACH-FUZZY [72]	Battery level, Crowdedness, Distance	–	Reduce energy consumption Maximize the lifetime	More overhead Death of sensor nodes	No	Yes	MATLAB	2017	Journal
CAFL [75]	The residual energy, node rank and the distance to the CHs.	Random	Lifetime, stability and received packets	–	No	Yes	Not mensionned	2017	Journal
ML-FL [76]	Energy, ETX, connectivity, channel capacity, RSRQ, bandwidth, link stability, hop count and mobility	–	Improve delay, PDR, energy and hop count.	ML-FL is tested in OMNET++ while OF-FL and OF0 are tested in cooja	No	Yes	OMNeT++ Windows 7	2017	Journal
[77]	Energy priorities, the distance to the sink and the centric cluster, cluster heads	Random	Increase in terms of the network lifetime reduce energy	Neglect another metric as overhead, PDR...	No	Yes	MATLAB	2013	Journal
OF-EC [39]	Hop count, ETX and Total Energy Consumption	Random and grid	Improve PDR, network lifetime, overhead, convergence time, latency and energy consumption	Provide high preferred parent change	No	Yes	Cooja Contiki OS	2018	Journal
DQCA-OF [80]	Hop Count, ETX, Consumed Energy	Random	Reducing the end-to-end delay and improving the QOS and lifetime	Low density of network	Yes	Yes	Contiki OS, Cooja, RFID Sensors	2018	Journal
CMOF [78]	ETX, Latency	Random	Improve network reliability and QOS Reduce congestion	Low density of network Compared to the standard MRHOF	No	Yes	Contiki OS, Cooja	2018	Conference
FLEA-RPL [79]	ETX, Load Traffic, and Residual Energy	Random	Improve network lifetime, and PDR Reduce end-to-end delay	The efficiency of the FLEA-RPL is not shown in terms of load balancing and overhead	No	Yes	Contiki OS, Cooja	2018	Journal

Table 8
Objective Functions-related research based on composite metrics in the context awareness approach.

OFs	Metrics	Method	topology	Improvement	Shortcoming	Experiment	Simulation	Simulator	Year	Publication
CAOF [81]	Nodes' capabilities, resources, and location	Context-Awarness	Manual	Best delivery ratio, Increase network lifetime, fairness in resource exploitation	Compared only to OF0	No	Yes	Contiki OS Cooja	2014	Forum
SCAOF [83]	Energy-aware, reliability-aware, robustness-aware and resource-aware	Scalable Context-Aware	Star	High lifetime, efficiency and reliability	Compared to the standard RPL Use a low density	Yes	Yes	Contiki OS Cooja testbed IWoTCore	2015	Journal
CA-OF [84]	ETX Buffer Occupancy (BO)	Congestion Aware	Manual	-choose the the least congested path through less congested nodes. -improves PDR, throughput and energy consumption.	Compared only to OFs using single metrics	No	Yes	Contiki OS cooja	2016	Conference

sensitive control applications in a Wireless Sensor Network (WSN). The OF used is the estimated EED, is based on two main routing metrics additively combined, which are the Processing Delay Metric (ProcDelayM) and the Path Delay Metric (PathDelayM). The first metric present the cumulative processing delays up to the sink while the second one is the cumulative link delays up to the sink. However, these new OF provide two main issues: high estimation accuracy and high overhead. To overcome these problems, the authors present another enhancement RA-EEDEEM (RPL Adaptation of End-to-End Delay Estimation Mechanism), designed to support and to balance the rate of the DIO messages while it neglects both DAO and DIS messages. RA-EEDEM improves the EED estimation accuracy in addition to reducing average EED and Packet reception ratio (PRR). However, this proposal has not considered some metrics such as the convergence time and energy consumption to prove its efficiency.

Another optimization of the objective function is presented in [91], the authors suggest a composite routing metric considering reliability and using the ETX metric as well as energy consumption. They introduce a new routing metric called Lifetime and Latency Aggregateable Metric (L2AM). This metric is based on the context awareness and resource limitations additively combined with the link quality, it allows balancing the consumption of energy during the DODAG construction and then extending the network lifetime. Compared to the standard ETX, L2AM provides high network lifetime, due to the energy consumption equally spent by nodes and the link reliability.

To optimize the network lifetime, authors in [92] propose a new energy aware and load balancing protocol (EL-RPL). Additively combined, load, battery depletion index (BDI) and expected transmission count (ETX) are used as criteria for parent selection. The route that provides the low value of the combination of the three metrics is considered as the optimal path to reach the destination. EL-RPL improves the PDR by up 2–4% and the network lifetime by up 8–12% compared to candidate improvement namely RER (BDI) RPL and fuzzy logic based RPL (OF-FL RPL). However, the comparison between EL-RPL and OF-FL still very constrained due to the use of a different methodology, namely the fuzzy logic, which needs more calculation process than the additive approach.

Using additive combination, authors in [93] propose an improvement of RPL in smart grid based on parent oriented (PO) and interface oriented solutions. Authors suggest a hybrid metric that considers three parameters in the rank computation: the rank of the potential parent (R (p)), the link quality level (LQL) and the expected transmission time (ET T). Compared to the single interface, the results show that PO and IO solutions improve the routing protocol by performing better in terms of parent changes, end-to-end delay, and PDR. However, these solutions do not ensure reliability and latency since they do not consider the duplicated packets that may be transmitted in the network. Authors in [95] propose a new combination of metrics used by RPL-based OF. The parent rank is calculated using the ratio of service rate to arrival rate and the ratio of queue length to buffer length. A path with a low value of this metric means that the route can be selected. The proposed approach improves the end-to-end delay compared to AODV. Nevertheless, some metrics were not considered for such as energy consumption and overhead.

One of the RPL issues is network congestion. To overcome this problem, authors in [94] propose a new Congestion-aware routing protocol (CoAR) using multi-criteria for the parent selection decision. To detect congestion, CoAR uses an adaptive mechanism based on the current queue occupancy and the traffic load variation, it uses a new congestion-aware objective function (CoA-OF) to select the best parent. This new CoA-OF uses multi-criteria decision-making (MCDM) technique that considers three main metrics namely ETX, queue utilization (QU) and Residual Energy. By this way, the node is allowed to avoid congestion situation and eliminate persistent ones by creating an alternative path toward destination. That the new CoAR retains high reliability under low traffic while aware of network under high traffic. In addition, it improves the end-to-end delay, throughput, PRR, packet loss, and energy consumption. In contrast, CoAR was designed to support only static network, which makes it less suitable for mobile environment. A summary of the different studies related to additive and lexical methods are summarized in Table 9.

Table 9
Objective Functions-related research based on composite metrics using additive/lexical approaches.

OFs	Metrics	Method	Topology	Improvement	Shortcoming	Experiment	Simulation	Simulator	Year	Publication
PEOF **PEOF2** [86]	ETX, remaining energy	Combination	Symmetric and Asymmetric	extended the lifetime equalized the energy consumption	Similar packet delivery ratio than MRHOF Compared only to the standard MRHOF	No	Yes	Contiki OS Cooja	2015	Conference
ENG+HC [87]	HC, Remaining Energy, ETX, PFI	The combination and single metrics	Grid	ENG+HC: reduce power and lost a packet With ENG: not consider a destination With HC: minimize latency, energy efficiency, and PDR	No consideration of link metrics With PFI: no retransmission is a guarantee	No	Yes	J-Sim v1.3	2014	Congress
PER-HOP OF [88]	Hop Count	Resolve the problem of a long single hop	–	Low latency High PDR Low energy	Consume more energy than MRHOF and OF0 in a small network	No	Yes	Contiki OS Cooja	2014	Conference
EEQ [89]	ETX, Energy, Queue Length	Additive Combination	Random	Low Overhead	One parameter is not sufficient for assessment Compared to the standards	No	Yes	Contiki OS Cooja	2019	Conference
RA-EEDEM [90]	Processing Delay and the Path Delay Metrics	Additive	Grid	improves the EED estimation accuracy reduce average EED and Packet reception ratio (PRR)	Not consider convergence time and energy consumption	No	Yes	Contiki OS Cooja	2014	Symposium
L2AM [91]	ETX, energy consumption	Additive	Manual	Increase lifetime	Compared only to the standard ETX	No	Yes	ad-hoc wireless network	2014	Conference
EL-RPL [92]	Load, battery depletion index (BDI) and expected transmission count (ETX)	Additive	Random	Improve PDR and lifetime	Compared with different method	No	Yes	Contiki OS Cooja	2018	Journal
PO, IO [93]	Rank, LQL, ETT	Additive	Hybrid	Improve parent change, end-to-end delay, and PDR	Don't ensure reliability and latency	No	Yes	Riverbed Modeler 18.5	2018	Conference
[95]	The ratio of service rate to arrival rate and the ratio of queue length to buffer length	Additive	Random	Improve end-to-end delay	Use only one parameter for evaluation	No	Yes	Opnet simulator.	2014	Conference
CoAR, CoA-OF [94]	ETX, QU, and RE	multi-creteria decision-making (MCDM) technique	Grid	Improve delay, PRR, packet loss, throughput, and energy consumption	It is not designed for mobile environment	No	Yes	Contiki OS, Cooja	2018	Journal

5.3.2.4. Multi-path routing protocol approaches. The authors in [96] treat the use of multiple instances by the RPL protocol. They focus on the limits of RPL when it does not specify the choice of the instance by nodes, which has an impact on the network performances. They propose a new Cooperative RPL called C-RPL where nodes follow a specific cooperative strategy to choose an instance within candidate ones. The proposed strategy considers the selfish behaviuor of nodes, the instance creates an alliance based on a compromise that considers the performance and the energy consumption provided by these alliances. Inspired from the game theory, the authors conclude that the proposed solution for WSN cooperative problem [97] using the prisoner's dilemma game [98] may be a solution of the same problem of RPL Instance. They consider that when using the sink node as root, the instances do not cooperate. In addition, they use multiple objective functions to measure the fairness of networks with multiple instances. The authors conclude that C-RPL allows creating the instance using a proper objective function and according to the network requirements. Moreover, C-RPL increases the number of the instance with a low density while it reduces the number of instances in a high density in order to decrease the consumption of the network and avoid the congestion. Furthermore, the C-RPL balances the fairness of the network in terms of energy consumption and performance with coexistence of multiple objective functions in the network. Since the proposed C-RPL considers the energy efficiency with the cooperative instance, they do not consider the Reliability by choosing a link metric.

Sousa et al. designed in [99] an Energy Efficient and Path Reliability Aware Objective Function (ERAOF) for IoT applications that require energy efficiency and reliability in data transmission. The main enhancement in this proposal is related to the composition of two metrics according to the additive metric: Expected Transmission Count (ETX) and Consumed Energy (CE). This OF can increase the packet delivery ratio while keeping effective energy consumption and use a low number of hop count to reach the destination. However, this study did not show the impact of this composition on the other network metrics as lifetime, convergence time, parent change and latency. In addition, it is compared only to the standard OFs. The use of any composition must be studied in a wide range to check if it allows overcoming the limitation of one metric approach.

In [15], Iova et al. proposed a new approach where they aim to increase network reliability and to balance the energy consumption simultaneously. They designed a new metric called the Expected Lifetime (ELT) metric [100]. It allows estimating how much time a node has to live before it runs out of energy. This metric is applied to the standard RPL protocol based on multipath routing. The diversity of path makes the network more reliable and increases the quality of service. However, there is an additional delay in transmitting the generated packets. It is due to congestion at the nodes that are responsible for transmitting.

Zhao et al. proposed in [101] a hybrid, energy-efficient cluster-parent based RPL routing called HECRPL. They aim at achieving energy efficiency, fairness, and reliability at the same time. The network is divided into a set of clusters. First, each node selects an optimal set of forwarders as its cluster-parent-set (CPS). Then, they compute the end-to-end transmission cost for a node through its optimal CPS (ECCPS) to select the best forwarder. The proposed solution integrates five major features to improve RPL. First, the top-down method to select the cluster-parent-set to minimize energy. Second, node coordination based on overhearing to avoid duplications. Third, the selection priority of a CPS based on a combination of residual energy and ETX routing metrics. Then, the recovery scheme to detect and retransmit lost packets. Finally, re-definition of transmission power to save energy, and improve network capacity. Compared to the standard RPL, HECRPL improves the network lifetime and increases reliability.

In [102], Weisheng Tang et al. propose a congestion avoidance and a multipath routing protocol using a composite routing metric. The authors propose a new routing metric called CA-RPL. The new routing metric is based on a combination of the ETX, the number of packets received by the node, the rank, and the minimized delay metric, which represents the whole duration for a packet to reach the sink node. Compared to the standard RPL, the new CA-RPL improves the network performances in terms of Packet Reception Number (PRN) and Throughput, packet loss rate, and latency. In most scenarios, the nodes are energy constrained, but here there is an absence of energy-aware metric. Therefore, this approach might not ensure a long lifetime of the network.

To optimize RPL protocol with the smart grid requirements in terms of Quality of Service (QoS), authors in [103] propose a new objective function called OFQS that uses a multi-objective metric (mOFQS). The mOFQS uses the ETX, delay and power state additively combined. This new OF takes into consideration the number of the instance that it adapts dynamically to offer QOS differentiation. This new OFQS adopts some functionalities of MRHOF where it keeps the use of hysteresis mechanism to avoid routing instabilities and decrease the parent switches. Compared to the standard OFs namely MRHOF and OF0 using multiple instances, OFQS improves the network lifetime, PDR and the End-to-End delay. In addition, OFQS balances traffic load among the nodes. Considering a set of OFs improvements, the comparison of OFQS with only the standard OFs reduces its efficiency.

In [104] The authors treat the multi-gateway ad-hoc networks by designing a multi objective function using available bandwidth, buffer occupancy, delay, and ETX in addition to the hop count routing metrics. The combined metrics are divided into two considerations: greedy or end-to-end approaches. The authors study the impact of the duty-cycling, traffic load and the number of gateways. The simulation shows three main results: the first one is that the greedy approach improves the network performance in the absence of a duty cycle mechanism. The second is the proposed OFs acts similarly in network congestion. Finally, the end-to-end approach and the shortest hop-count offer good performances in the presence of the duty-cycle mechanism. The proposed OFs was tested in terms of PDR, delay and retransmission packets while it neglects other important metrics as lifetime, energy consumption

Authors in [105] propose the different implementation of RPL in the WSN network based on its objective function. They choose as metrics for OFs; the available bandwidth, the delay, the MAC layer queue occupancy (the number of frames in the MAC layer queue), and the ETX as the tie-breaking metrics and combined with the hop count metric. The implementations adopt two main approaches, the greedy and end-to-end approaches. Compared to standard RPL based on minimum hop count, the OFs based on tie-breaking metrics improve the RPL by increasing the packet delivery ratio (PDR) by up to 25% and decreasing the number of retransmissions by up to 65%. In addition, the greedy approach gives a low improvement than end-to-end delay approach. Moreover, the use of multiple sinks has an impact on the RPL performances where they well improved. In contrast, in a congestion state, the protocols performed similarly. Another multi-objective function was proposed in [106]. The authors propose a combination of three metrics namely ETX, HC, and Residual Energy. The resulting new objective function, Analytical Hierarchy Processes OF (AHP-OF) provides a multi-option that can be adopted by the algorithm to make a decision based on synthesis results. Compared to the standard MRHOF and OF0, AHP-OF reduces the power consumption and balances the traffic load between nodes in the network. However, AHP-OF needs to be compared to multi-metric candidate OFs.

To maximize the lifetime of the network, authors in [107] propose a new extension of RPL based on adaptive multipath traffic load algorithms. It allows adjusting and delivering traffic within multipath in correlation with the network requirements. This algorithm combines the steepest descent method and Newton's for optimal distribution. Using iteration test, this method allows selecting best group's weights to deliver traffic. The authors propose then to reduce the end-to-end delay by adopting the data forwarding model that computes the listening time based on traffic distribution algorithm using greedy. However, even with the balance of the consumption energy of nodes still, nodes that are near to the sink consume more energy and may lead to network failure. A comparison study of different proposed enhancement using multi-parent has been made in Table 10.

5.3.2.5. Other OF extensions. To resolve the problem of load balancing produced by bottleneck nodes, authors in [13] propose an objective function that overcomes the network failure caused by nodes that undergo their energy very faster. The new LB-OF allows to equally distribute the number of children nodes for bottleneck preferred parent, which in turn increases the network lifetime. LB-OF is based on injecting a parent ID into the DIO messages. Once nodes receive their first DIO message, they select the sender as the best parent and then calculate their own rank according to the OF operation. The use of LB-OF leads to overcome any extra overhead and then balance the traffic in the network. The results show that LB-OF outperforms the standard OFs in terms of lifetime, PDR and energy consumption. The only limit of this approach is it is not compared to a candidate amelioration that considers also the load balancing traffic. Similarly, authors in [108] propose an optimization of load balancing for RPL through an emergency response based on Q-learning (LBO-QL). The main goal is to preserve a similar number of child situated in different links to balance the distribution through nodes and links as well. In addition, this LBO–OF optimizes traffic between multi-DODAG where a framework was developed to mitigate communication through different border router from different DODAGs. Moreover, the authors highlight the concept of the mobility where they propose a Q-learning computation that increases energy and control traffic to consider the frequency change of DODAG building. Alike, authors in [109] propose a Traffic Aware Objective Function (TAOF). Through modification of the DIO messages format, the authors inserted a new routing metric called Packet Transmission Rate (PTR) that measures and returns the packets count transmitted by each node in a specific time. This modification into the DAG Metric Container leads to no extra traffic. The TAOF improve the network performances by increasing the PDR and make it more stable by reducing the number of parent changes. However, the new OF is studied using a low density composed of 12 nodes, which is not sufficient to confirm that results can be extrapolated to the high density case.

Another investigation of the congestion and the load balancing problems is presented in [110,111]. The authors propose a new RPL based on queue utilization (QU-RPL) that allows avoiding lost packets due to the congestion, especially with heavy traffic. This solution enables nodes to choose the best parent according to the queue utilization and their distance to the border router, which leads to balancing the traffic overflow. Through experiments, the proposed solution decreases the queue loss by up 84% and enhance the PDR compared to the standard RPL. This solution is Compared only to the standard RPL, while it neglects other important metrics such as the energy consumption, lifetime, and the first node to die. Similarly, authors in [112] propose a new queue-base burst transmission MAC protocol (Q-BT). This new protocol allows resolving the asynchronous problem related to both hidden terminal and channel contention of duty-cycle MAC protocol. Using queue length information, the protocol provides both asynchronous duty-cycle and burst transmission of neighbour packets even with coexistence of node and its hidden nodes on the same channel. The results show that the proposed approach improves the performances in terms of duty-cycle and the packet reception ratio by up 59.1%, and 70.2% respectively compared the candidate approach. This solution focuses on nodes transmission with no consideration of the impact of the objective function on node behaviour when parent selection is provided.

Furthermore, security remains one of the main issues when assessing network performances [113]. It is worth noting that we exclude from the current survey dedicated efforts on security, data protection, and privacy, as it is commonly done in the community nowadays. Security issues are generally better covered in dedicated surveys such as [28,114–116].

Authors in [117] exploit the vulnerability that an objective function can introduce using the calculated rank. They propose a new rank attack that modifies the OF based on rank value. The proposed attack called Rank Attack using the Objective Function (RAOF) allows malicious nodes to build a path through these attacking nodes by providing a false rank and a routing metric value. Through simulation, RAOF makes a simple attack on the network by selecting malicious nodes as preferred parent or forwarding nodes. As results, the RAOF decrease the PDR until 30% compared to the standard RPL. In addition, it increases the overhead and adds a more extra delay in the network.

To overcome the problem of instability due to the frequent change of route in the network, authors in [118] propose a hybrid objective function that considers both the channel adaptability and the stability provided by hop count and ETX routing metrics. The authors adopt two dynamic thresholds to maintain stability even with dynamic networks. The first one controls the link-based tolerance using the number of transmission per packet while the second one controls the stability based on the hop count metric. The simulation results show that the approach reduces the parent changes, the control traffic, and the energy consumption. Accordingly, the Hybrid solution increase the stability of the network with a long lifetime. However, in the first simulation, the authors set the threshold to zero where the proposed Hybrid solution provides lower improvement than the other metrics do. In contrast, with a threshold equal to 0.8, the Hybrid approach operates better and improves the network performances. The choice of this threshold value is not justified by authors, which permits to conclude that if this value changes it may affect the efficiency of the proposed Hybrid objective function.

To address the problem of power consumption and packet loss in a heavy network, authors in [119] suggest a set of amelioration to the RPL protocol. First, they propose a new objective function called CAOF that considers the context awareness. Second, they present a new routing metric called CARF that considers the remaining energy stats and the queue utilization of the parent chain. Finally, they present a new mechanism of parent selection based on the new routing metric CARF and avoiding routing loops. Through these ameliorations, the authors address three main problems that impact the RPL operations categorized as follows: first, the rank computation that not considers the previous parents of a node in succession. Second, the DODAG construction based on the smaller value of rank provided by candidate parents. This problem is seriously impacting the parent selection especially in high dynamic traffic, where the rank value may not reflect the last state of candidate neighbours. The Thundering Herd Phenomenon [120], where the small value of rank can attract a set of nodes including the child of other parents, makes the network instable. However, the proposed CLRPL is compared to the standard RPL, where CLRPL shows an improvement in terms of network lifetime, packet loss and overhead. To this end, the proposed CLRPL treats

Table 10
Objective Functions-related research based on composite metrics using the multipath approach.

OFs	Metrics	Method	Topology	Improvement	Shortcoming	Experiment	Simulation	Simulator	Year	Publication
ERAOF [99]	ETX and energy consumption	Additive composition	Grid	increase the packet delivery ratio keeping effective energy consumption and the use of a low number of hops. Thus,	Compared to the standard OF0 and MRHOF	No	Yes	Contiki OS Cooja	2017	Conference
ELT [15]	Expected lifetime	New routing metric basd bottlenecked nodes	Random	The network is more reliable, Increase the quality of services	Additional delay	No	Yes	WSnet	2015	Journal
HECRPL [101]	Remain energy, ETX,	Top down parent selection, Combined metrics Recovery scheme	Random	Save energy Increase lifetime	Compared only to the standard RPL	No	Yes	NS-3	2016	Journal
CA-RPL [102]	ETX, received packets, the rank, and the delay	Additive composition	Grid	decrease packet loss ratio and time delay	Compared to the standard RPL	No	Yes	Contiki OS Cooja	2015	Journal
OFQS [103]	ETX, delay and power state	-Additive combination -Multi instances	Random	improve the network lifetime, PDR and the End-to-End delay. balance traffic load among the nodes.	Compared only to the standard MRHOF and OF0	no	Yes	Cooja + MSPSIM	2017	Symposium
[104]	available bandwidth, buffer occupancy, delay, ETX and hop count	greedy and end-to-end approaches	Grid	- greedy approach improves network performance with no duty cycle mechanism. -the end-to-end approach and the shortest hop-count offer good performances with duty-cycle mechanism.	neglect other important metrics as lifetime, energy consumption	no	Yes	Cooja	*2017*	journal
[105]	Available bandwidth, delay, MAC layer queue occupancy, ETX and hop count	Combination based on greedy and end-to-end approaches	Random	Increase PDR, decrease ETX With multi-sink, both approaches act similarly	Neglect the convergence time, the lifetime, the number of parent change.	No	Yes	Contiki OS Cooja	2015	Conference
AHP-OF [106]	ETX, HC, and Residual Energy	Analytic Hierarchy Process (AHP)	Random	Reduce PC Balance the traffic load	Compared to the standard	No	Yes	Contiki OS, Cooja	2018	Conference
[107]	ETX, Residual Energy Traffic load Waiting time	steepest descent method and Newton's greedy	Random	Improve lifetime, reliability and the end-to-end delay	Node near to the sink still consume more energy	No	Yes	Contiki OS, Cooja	2017	Journal

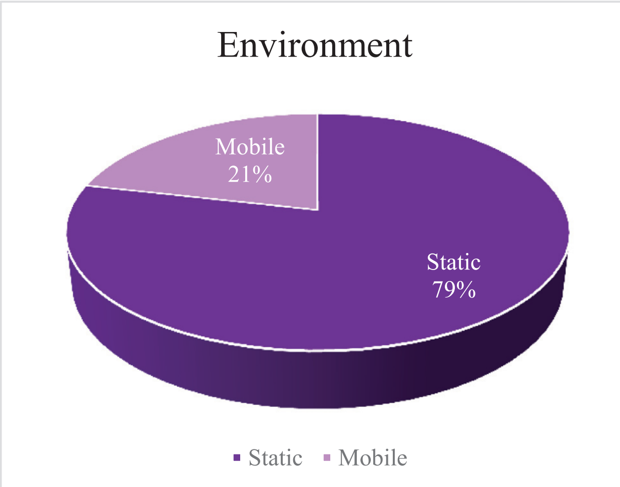


Fig. 10. Distribution of the different environment used for assessment.

a set of important context-aware and load balancing issues. It should be compared to a candidate solution that considers context aware [81] or load balancing [13] to showcase its efficiency which is degraded compared to the standard. In addition, the nomination of CAOF objective function was already treated in [81], which leads to a conflict of interest.

A smart energy efficient objective function (SEEOF) was proposed in [121] to resolve IoT smart metering applications limits in terms of battery power and computing functionalities. SEEOF considers the energy efficiency in the goal to extend network lifetime. It is based on a composite metrics that consider links quality based on the ETX metric and node energy using the Estimated Remaining Life Time (ERLT). The proposed OF was compared to the standard MRHOF based on ETX. The simulation results show that the proposed SEEOF extend the network lifetime by up 27%. In addition, it allows balancing the energy consumed by all nodes in the network. However, the proposed OF was simulated using a very low density around 18 nodes, which is not efficient to conclude that SEEOF is better than MRHOF, especially in high density. In addition, no candidate OF was used in comparison instead of the standard one. The different extension of RPL are summarized in Table 11.

5.4. Statistics, analysis, and discussion for OFs enhancement

In this subsection, we provide a statistical analysis of the research papers that have investigated RPL based on the evaluation methods and publications.

5.4.1. By evaluation methods

By considering the proposed enhancement of the RPL, only 15% of reviewed publications use the objective functions based on single metrics while more than 80% propose a combination of a set of routing metrics (Fig. 11). This is due to the problem related to the use of single metrics, where the objective function based on single metric choose the optimal path by considering adequate metric while it degrades others. For this reason, many research studies are conducted to propose a combination, especially between node and link metrics using different approaches. In Fig. 12, we notice that 27% of reviewed papers use the fuzzy logic method and 24% use the additive/lexical method. In addition, RPL research community addressed the problem of the objective function by considering other aspects such as the context awareness (7%) and multi-path (22%) issues. However there still 20% for other propositions of metric combination that consider load balancing, queue utilization, and rank attack.

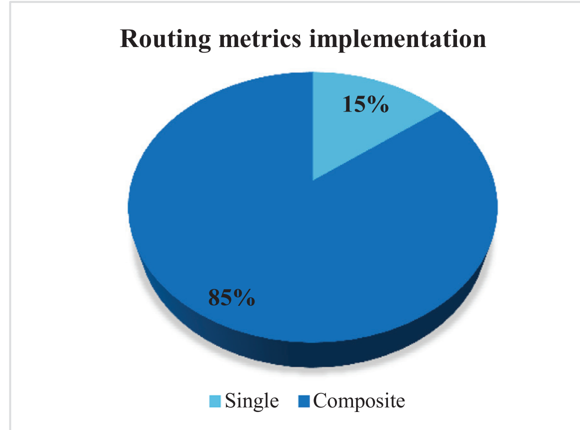


Fig. 11. Distribution of the routing metrics implementations.

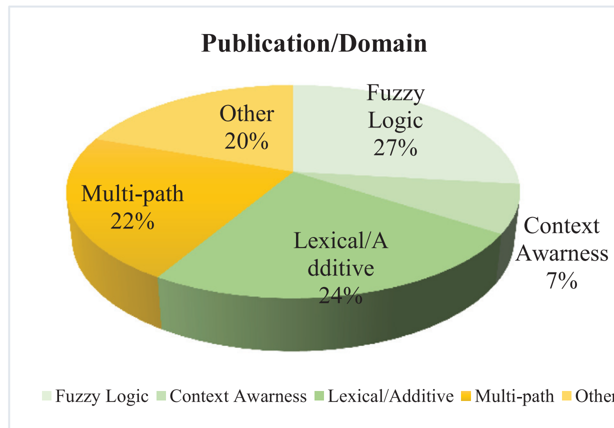


Fig. 12. Distribution of the enhancement publications per domain.

5.4.2. By implementation and simulator

Through our analysis, we conclude that most of the studied paper focuse on simulations instead of experiments, which can be explained by the availability of the software in addition to its easier accessibility. More than 80% from the reviewed papers (Fig. 13) use simulations while only 14% is for experiments, which is unsatisfactory. The big effort dedicated to making RPL a standard was

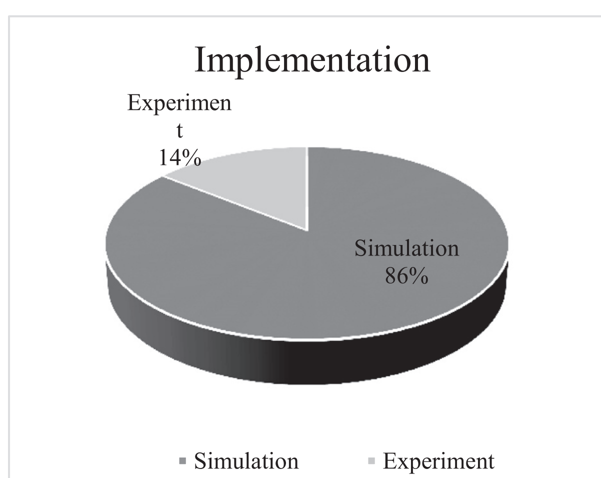


Fig. 13. Distribution of the enhancement implementations.

Table 11
Objective Functions-related research based on composite metrics using other approaches.

OFs	Metrics	Method	topology	Improvement	Shortcoming	Experiment	Simulation	Simulator	Year	Publication
LB-OF [13]	–	ID parent injection into the DIO messages	random	Improve lifetime, PDR and energy consumption	Compared only to the standard	No	Yes	Contiki OS Cooja	2016	Conference
LBO-QL [108]	Load balancing	Q- learning	random	Improve PDR, Energy, and overhead	Compared to OFs that use single metric	No	Yes	Contiki OS, Cooja	2018	Journal
TAOF [109]	Load Balancing	DAG Metric Container modification	random	Improve PDR, reduce Parent Change	Use very low density	No	Yes	Contiki OS, Cooja	2018	Conference
QU-RPL [110,111]	Queue utilization, hop count	–	Manual	decrease the queue loss by up 84% and enhance the PDR compared to the standard RPL	Compared to the standard RPL	yes	No	Tiny OS PC, TelosB radio	2016 2015	Journal conference
RAOF [117]	ETX	Rank attack	random	Decrease PDR Increase overhead and delay	Compared only to the standard RPL	No	Yes	Contiki OS cooja	2016	Conference
Hybrid [118]	ETX, Hop count	Combination based on threshold	–	More stability Long lifetime	Choice of δ threshold is not justified	No	Yes	Contiki OS cooja	2017	Conference
CLRPL [119]	Remain energy, queue utilization, and context awarness	Combination based on new metric CARF	manual	Increase lifetime Decrease packet loss and overhead	Compared only to the standard RPL	No	Yes	Contiki OS Cooja	2018	Journal
SEEOF [121]	Estimated Remaining Life Time (ERLT) and ETX	Combination based on new metric ERLT	Random	Increase lifetime Balance the energy consumption	Use only low density Compared only to the standard	No	Yes	Contiki OS Cooja	2017	Summit

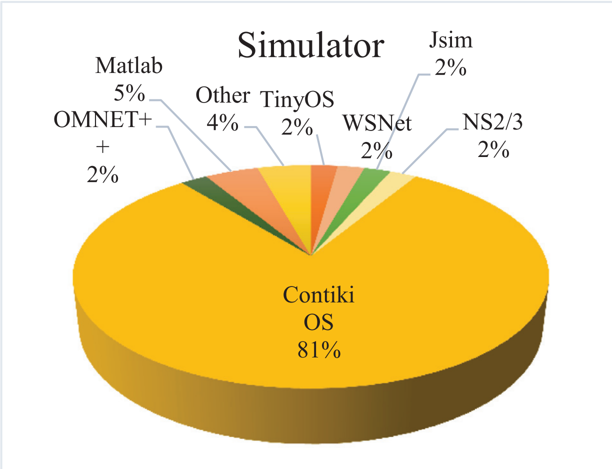


Fig. 14. Distribution of different simulators used for implementations.

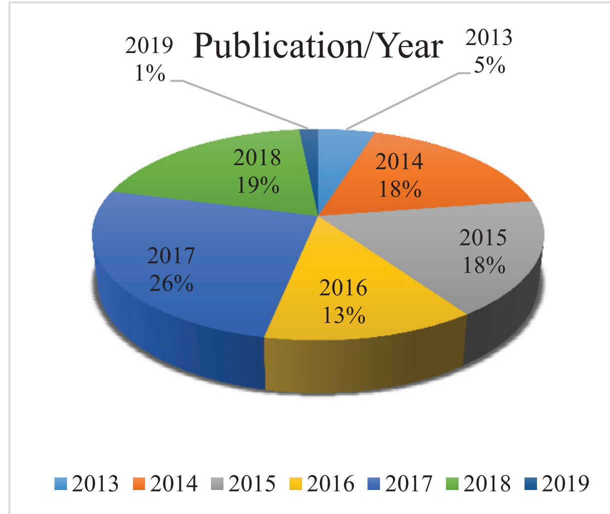


Fig. 15. Distribution of publications per years between 2013–2019.

on adopting this protocol to be optimal with IPv6 implementations and real deployments. This big difference of (72%) can be due to the low resources in terms of the financial laboratory of research and the high cost of hardware. We notice that the evaluation based only on simulations do not reflect the reality since it does not consider a set of constraints such as climate change, naturel obstacles and human interactions. As shown in Fig. 13, the hardware used for experiments are 'Zigduino' devices, 'ATmega 128RFA1' microcontroller, 'real indoor WSN', 'IWoTcore plus' testbed using the Contiki operating System in addition to 'TelosB' radio using Tiny operating system. Each implantation is used only one time in the reviewed papers. This situation invites once again researchers interested in RPL, to focus more on real use cases.

ContikiOS is considered as the widely used software in the WSN and LLN community as shown in Fig. 14. It can be justified by the fact that ContikiOS is an open source and the most popular operating system used to assess the proposed enhancement. In addition to ContikiOS, some implementations use the TinyOS the first candidate of ContikiOS in developing WSN and LLNs requirements when it comes to RPL. The majority of objective function based improvements of RPL is developed based on Contiki OS by up 80%, while only 5% use MATLAB and 2% used TinyOS, OMNET++, Jsim, WSNet, and NS2/3. Compared to [21], we can distinguish an increase of using Cooja simulator by research community by up 18% with a value of 81% instead of 63% in [21]. This is due to its flexibility regarding any modification in its core configuration as well as the objective functions with no 'side effect' on the other components of RPL. In addition, ns2/ns3 presents a percentage of 12% in [21] while in our study is 2% and 5% for MATLAB instead of 3%.

5.4.3. By publication

After RPL standardization in RFC6550 and the two objective functions, namely MRHOF in RFC6719 and OF0 in RFC6552, many works tried to improve this protocol in various domains. In 2013, only 5% of the reviewed papers propose an improvement of objective functions as shown in Fig. 15. Since then, this number increased to reach 18% in 2014–2015. However, in 2016 this number decreased by 5% compared to 2014–2015. This result can be explained by the great number of enhanced OFs published between 2013 and 2015, which pushed the research community to focus on other components of RPL such as trickle timer and DODAG construction. Furthermore, in 2017 the focus on improving the objective function attracted many researchers, which increased the number of publications to reach 26% and continued with 19% until October 2018. To date, the number of publications in 2019 constitutes only 1% and counting. We believe that more research publications will appear in the coming years which can be explained by the fact that RPL is still a relevant protocol adopted by the current IoT technologies.

6. Challenges and open issues

The concept of RPL reposes on maintaining and building its topology using the process of rank computation. It uses the control messages to support the different traffic, considering at the same time the LLNs requirements and network environment constraints. Finding an efficient mechanism that helps building RPL topology faster with low failures, and supports different traffic patterns remains one of the big challenges of this protocol.

As mentioned earlier, RPL supports different traffic such as MP2P, P2P, and P2MP. The routing optimizes the use of MP2P when building DODAG topology. In contrast, the use of P2P and P2MP provides some issues related to the lossless of the links and the long delay; especially for P2P communications where nodes need a border router to transmit. This issue was highlighted in [122] where authors addressed the problem of various traffic patterns. They proposed a new implementation called DT-RPL. To support different traffics, DT-RPL provides fast routes updates using dynamic link. This solution makes routes with dynamic link to be more stable and reliable regardless of the traffic. The proposed solution did not take into consideration the neighbor's discovery used in P2P communication, which constitutes another issue of RPL. In high densities, nodes need to transmit information for DODAG building, which increases the energy cost. Therefore, reaching the goal of good reliability with energy efficiency is still a challenging solution. Thus, preserving energy while providing good reliability is the main goal that the routing protocol tries to achieve. By using a specific objective function to select the best parents, the routing protocol needs to carefully choose the adequate routing metrics as criteria. These metrics should consider the dynamicity and lossless of both links and nodes. As shown in the analysis section, the use of single metrics provides some constraints by insuring the good quality of few network parameters while degrading others. In addition, the use of combined metrics is a promising direction that some studies are trying to fix in order to find the optimal composition. Due to the memory limitation of nodes in LLNs, the high density of networks provides a set of constraints: firstly, the network congestion is caused by the high traffic and low buffer size of LLNs nodes. Moreover, the congestion reduces the channel quality and leads to an increase in packet loss, which in turn increases the delay. With the absence of a good congestion control mechanism that considers at the same time the LLNs characteristics, finding an efficient scheme that controls and detects congestion will be a very challenging solution. Only few research efforts have been made to avoid congestion using adjusting and re-routing traffic or using the multipath concepts [84,102,123] but still not sufficient to improve RPL in this context.

Two other challenges are considered in [124]: the network size and network density. The first challenge deals with keeping a stable topology when the network size increases. The authors propose an end-to-end mechanism that introduces new rules for DAO and DAO ACK transmission in addition to an ability to balance topology based on the routing table information sent periodically. The second challenge is how to preserve topology stability with an increase in the network density. The authors adopt new neighbour selection policy where only the best neighbours can be stored in the routing table. Through simulations, both mechanisms allow RPL to scale beyond the storage limitation of both numbers of neighbours and routes. Due to the limitation of the link rates of LLN, they offer more bandwidth when transmission of heavy traffic is needed. A solution, *PC-RPL* (Power Controlled RPL) [125], was proposed to limit this problem based on transmission power and topology construction following local rules. These rules regulate the impact of the routing distance, queue loss and link loss in a balanced way to reduce loss.

Another challenge of the objective function is the environment of implementation. As shown in Fig. 10, more than 70% of objective function assessment has been done in a static environment, while only 21% in mobile context. In addition, only few studies propose a solution for using an objective function with mobility [69,77]. However, in mobility, nodes tend to change their preferred parent dynamically with the change of the network topology. This problem causes more overhead and packet loss and more energy consumption. Finding a mechanism of preventing or detecting nodes movement with respect to the objective function specification constitutes the main challenge for LLNs networks. Another issue related to the use of the objective function is load balancing [126]. The LLNs nodes are distributed randomly in the network and they choose their preferred parent according to the leaf neighbor with the lowest rank. Nodes still transmit to this preferred parent especially in stationary topology, until it consumes its whole energy, which affects the network performances and reduces its lifetime.

Based on rank computation in choosing an optimal path is an insecure process. Nodes may be faced to any malicious node that can join the DODAG, which means that transmitted packets can be simply dropped or modified. Consequently, network attacks threats raise critical security and privacy concerns. Thus, many research efforts are required to ensure the security of LLNs networks.

7. Conclusion

In this survey, we focused on the objective function as the main component of the RPL routing protocol. We presented both the assessments and the enhancements made so far to overcome the limitations of the objective functions. First, we introduced the background of the routing metrics and their characteristics. Then, we highlighted the concept of the objective function used for the best path selection. Specifically, we reviewed a set of papers that reflect the research efforts made by the RPL community to improve the objective function. In particular, our survey presented the difference between the use of single and composite metrics and the weight of each one on the parent selection and the performances of the network. We noticed that more than 20% of the surveyed papers proposed an assessment of the standardized objective functions while 77% proposed an enhancement based on both single and composite metrics. The proposed enhancements were extensively evaluated through simulations (86%) and less by experiments (14%). Moreover, in the publications that are based on experimental evaluations, ContikiOS was the widely used simulator (81%). However, based on our observations, we concluded that a set of scenarios and implementations are yet to be fully exploited. The current survey invites researchers interested in RPL to focus more on real use cases and to investigate more the mobile context.

Declaration of Competing Interest

None.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.adhoc.2019.102001.

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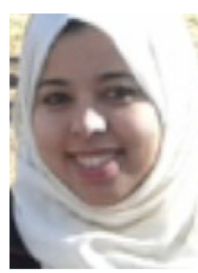

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