OF-ECF: A New Optimization of the Objective Function for Parent Selection in RPL

Hanane Lamaazi
Moulay Ismail University of Meknes, Faculty of Sciences, Meknes, Morocco
lamaazi.hanane@gmail.com

Adnan El Ahmadi
Ibn Tofail University, National School of Applied Sciences, Kenitra, Morocco
elahmadiadnan1@gmail.com

Nabil Benamar
Moulay Ismail University of Meknes, School of Technology, Meknes, Morocco
n.benamar@est.umi.ac.ma

Antonio J. Jara
University of Applied Sciences Western Switzerland (HES-SO) Sierre, Vallais, Switzerland
jara@ieee.org

***Abstract*—** The RPL routing protocol is designed to respond to the requirements of a large range of Low-power and Lossy Networks (LLNs). RPL uses an objective function (OF) to build the route toward a destination based on routing metrics. Considering only a single metric, some network performances can be improved while others may be degraded. In this paper, we present a flexible Objective Function based on Expected Transmission Count (ETX), Consumed Energy and Forwarding Delay (OF-ECF) built on a combination of metrics using an additive method. The main goal of this proposed solution is to balance energy consumption and minimize the average delay. To improve the reliability of the network, a flexible routing scheme that provides the diversity of paths and a higher availability is presented. Simulations results show that the new objective function OF-ECF outperforms the OF-FUZZY, and the standards OF0 and MRHOF. In terms of network lifetime and reliability.

Keywords- RPL, Objective Function, ETX, energy consumption, forwarding delay.

I. Introduction

Internet of Things (IoT) refers to the network of physical objects having the ability to communicate with each other in an ubiquitous way through different technologies [1]. They are used to ensure communication services in many application scenarios such as healthcare [2], industrial automation [3], [4], and smart homes [5]. However, sensor nodes are small and battery powered. Thus, changing their batteries is a very challenging task. Low power and Lossy Network (LLN) possess two key features: the limited resources of nodes and the lossy links between them. By considering these specific characteristics, Routing Over Low power and Lossy networks (ROLL) working group has initially proposed the IPv6 standard routing protocol for low power and lossy networks (RPL) in [6]. To provide significant flexibility for supporting various application requirements and quality of service (QoS) routing, RPL uses the objective function (OF) as one of its core functions [7]. The OF specifies the rules that a node has to follow to choose its preferred parent from different candidates [8]. However, each objective function takes the forwarding decision based on a single routing metric. Such a choice is not sufficient to ensure high performance; it guarantees only one property. Thus, the current paper proposes a new Flexible Objective Function based on three metrics namely, ETX, the Consumed Energy and the Forwarding Delay (OF-ECF). OF-ECF is designed for WSN applications that require reliability, energy-efficiency, and real-time guarantees.

The main contributions of the current study are as follows:

1. In contrast with the previous works [9] [10] [11], that aim to attend to the requirements of one application, we design a new flexible routing that requires reliability, energy-efficiency, and real-time guarantees.
2. A novel routing metric, which jointly considers node energy consumption, lossy rates of wireless links and the forwarding delay, is designed to optimally select the best forwarder node with the minimum energy consumption for data delivery.

The remainder of this paper is organized as follows: Section II presents an overview of the RPL routing protocol and the Objective Function. Section III is dedicated to related works on RPL. Section IV presents the design of our composite metric OF-ECF. Section V presents and analyses the simulation results. Finally, section VII concludes the paper and discusses the remaining challenges and perspectives.

II. RPL Overview

RPL is a distance vector IPv6 routing protocol for LLN designed by ROLL working group. It builds a destination-oriented directed acyclic graph (DODAG) according to an objective function and a set of metrics and constraints. The DODAG graph is routed to the sink node, which guarantees the communication between the network and the Internet. The RPL routing protocol defines a set of ICMPv6 control messages for the DODAG construction and maintenance. There are four principal messages: DIS, DIO, DAO, and DAO-ACK. DODAG Information Object (DIO) contains information that allows nodes to discover the instance, learn its configuration and select the preferred parent. A node sends a DODAG Information Solicitation (DIS) message to solicit for DIO packets from neighbours. DODAG Advertisement Object packets (DAO) are used to collect information about the topology. DAO-ACK is sent by a DAO recipient in response to a DAO message [12] [13].

Objective Function

The main role of RPL is the use of an objective function that allows choosing the optimal path toward the root. The OF specifies the rules that a node has to follow to choose its preferred parent from the candidate ones. It translates one or more metrics to a rank value. The node that provides the lowest rank is considered as the best parent to reach the destination. Two main OFs have been standardized by the IETF namely OF0 [9] and MRHOF [10]. The OF0 is based on the low number of hop count that a node provides while MRHOF uses the minimum number of expected transmission count metric. The nodes that offer a minimum hop count or low expected transmission count metric constitute the optimal route to the sink.

III. Related works

In this section, we review some relevant efforts made to improve the deployment of the objective function for RPL protocol based on different approaches.

Based on the Multi-path routing protocol approach, Sousa et al. designed in [14] an Energy Efficient and Path Reliability Aware Objective Function (ERAOF) for IoT applications that require energy efficiency and reliability in data transmission. Using additive metric; ETX and Consumed Energy (CE), this objective function can increase the packet delivery ratio while keeping an effective energy consumption. However, this study did not show the impact of this composition on the other network metrics.

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. 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 the path makes the network more reliable and increases the quality of service. However, there is an additional delay in transmitting packets generated. It is due to congestion at the nodes that are responsible for transmitting. In [16], Weisheng Tang et al. propose a congestion avoidance and a multipath routing protocol using a composite routing metric. It combines all of the ETX, the number of packets received by the node, the rank, and the minimized delay metric. 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.

In [17], Kamgueu et al. proposed an objective function that combines several metrics. They used the fuzzy logic method to merge ETX, node's remaining energy and delay into one composite metric. The solution of Kamgueu et al. outperformed the ETX based routing on packet loss ratio, energy consumption distribution, and end-to-end delay. Another enhancement related to the composite metric based on a fuzzy logic method is proposed in [18]. Lamaazi et. al. considered in their enhancement both the link metric and node metrics. The main improvements are the equalization of distribution of energy consumption, high Packet Delivery Ratio (PDR) value and low overhead compared to the candidate OFs. Otherwise, it provides a high probability of parent change.

IV. The proposed OF-ECF

A. Problem Statement

By default, RPL uses a single primary metric, which performs poorly in some scenarios where some constraints must be handled. To overcome this issue, we propose in the current paper a new flexible Objective Function based on ETX, Consumed energy and Forwarding delay (OF-ECF) using additive composition method. This approach allows building a new composite metric that nodes adopt to select the best parent. It returns one decisive value instead of various metric decisions. The following subsection defines the metrics of interest.

B. Metrics of interests

- **ETX:** The ETX of a path is defined as the summation of the ETX of all links along the path and on each link; it expresses the number of link-layer transmissions required for the successful delivery of a message to the next hop neighbour. The ETX metric value is calculated according to [19]:

$$ETX = \frac{1}{D_f \times D_r} \qquad \textbf{(1)}$$

$\mathbf{D_f}$ is the measured probability that a packet is received by the neighbour.

$\mathbf{D_r}$ is the calculated probability that the acknowledgment packet is successfully received.

- **Forwarding delay (Delay)**: It is the estimated time for a packet to be retransmitted to the next forwarder. The summation of forwarding delays constitutes the total delay. Delay is a primary routing metric that increases strictly from the sink node towards the sensor nodes. The best forwarder is the node that provides a path with lower delay. We calculated the delay at the node 'i' through the formula [11]:

$$Delay(i, root) = \begin{cases} 0 & if \quad root \\ Delay(p, root) + FD(i, p) & if \quad not\ root \end{cases} \quad (2)$$

Where p is a candidate parent and $FD(i, p)$ is the forwarding delay between the current node i and its candidate parent.

- **Consumed energy (CE)**: It is the consumed energy by a node at time t. Each node generates a number of ticks according to its state. It is calculated according to the formula [19] [20]:

$$E(mJ) = \frac{3 \times (TX \times 19.5 + RX \times 21.8 + CPU \times 1.8 + LPM \times 0.0545)}{32768} \quad (3)$$

CPU is activated whenever the node is active.

LPM state is activated when the node goes to Low power mode.

TX and **RX** are the values of ticks when the node is transmitting or listening [21].

Algorithm 1 illustrates the process of calculating the new objective function (OF-ECF)

Algorithm 1: preferred parent selection based on composite metrics

```
Input: A set CANDIDATE_PARENT of parents
Output: The best parent in the set

begin
best_parent ← CANDIDATE_PARENT(first_parent)
foreach p in CANDIDATE_PARENT
    p1 ← best_parent
    p2 ← p
    composite_metric_1 ← w_energy * p1.energy + w_etx * p1.etx +
    w_delay * p1.delay
    composite_metric_2 ← w_energy * p2.energy + w_etx * p2.etx +
    w_delay * p2.delay
    if composite_metric_1 < composite_metric_2 then
        best_parent ← p2
    end
end
Send (DAO message)
return best_parent
end
```

Each primary metric should hold the same order relation (either maximization or minimization) so that the produced composite additive routing metric makes sense. Furthermore, we define the weights of each primary metric $\mathbf{w}_{ETX}$, $\mathbf{w}_{CE}$, and $\mathbf{w}_{Delay}$ to be multiplied to ETX, CE, and Delay where the sum of weights ($\sum w_i$) must be equal to 1. The formula of the composite metric is given by:

$$F(ETX, CE, Delay) = \frac{w_{ETX} \times ETX + w_{CE} \times CE + w_{Delay} \times Delay}{\sum w_i} \quad (4)$$

The choice of the weights $\mathbf{w}_{ETX}$, $\mathbf{w}_{CE}$, and $\mathbf{w}_{Delay}$ depend on the application requirements and on the type of traffic (for instance, for emergency applications the delay is more important than the other metrics).

V. Simulation setup and Results

A. Simulation environment

In the current study, we used Cooja simulator running on Contiki OS [22]. It is an open source operating system dedicated to IoT applications. We use sky motes as a sensor platform. Table 2 present the RPL configuration used in our simulations. The simulation scenarios consider 12, 24, 36 and 48 nodes deployed randomly. The sink node is located in the top center while the sender nodes are located randomly in the simulation area. All simulations take 1000s long. The reported results reflect the average over 20 runs and stay within 0.1 – 0.2 of the sample mean when subjected to 95% of the confidence interval. We evaluated our proposed solution OF-ECF in comparison with three objective functions available in the related literature, namely the FUZZY objective function [17], OF0 [9] and MRHOF [10].

Table 1: Simulation Setup

Simulation Setup	
Simulator	Cooja
Mote type	Sky mote
Simulation area	200 m × 200 m
Interference range	90 m
Transmission range	45 m
Data Rate	1pkt/min
Radio Medium	Unit Disk Graph Medium (UDGM)
TX, RX	100%
Simulation Duration	1000s
Number of nodes	12 – 24 – 36 – 48
MAC Layer	IEEE 802.15.4
Radio Duty Cycle	ContikiMAC
Energy model	CC2420

B. Metrics of interest

To evaluate our proposed approach, we measured the following metrics:

-Convergence time: It is the time when all the nodes join the network

-Packet Delivery Ratio: It is the ratio of total received packets (at sink node) to the total sent packets overall network.

-Network lifetime: It is the duration before the first node depletes its energy and dies.

-Overhead: It is the sum of DIO, DIS, and DAO messages.

-Consumed energy: It is the energy spend by nodes in the network

C. Simulation results

1) Convergence time

To investigate the real-time property, we calculated the convergence time where we measure the time at which the DAG is completely constructed and all the nodes have joined the network. A short convergence time means that the routing scheme allows the nodes to quickly join the network DAG. Figure 1 shows the convergence time variations with network size. We compared between OF-ECF, FUZZY, MRHOF and OF0 objective functions.

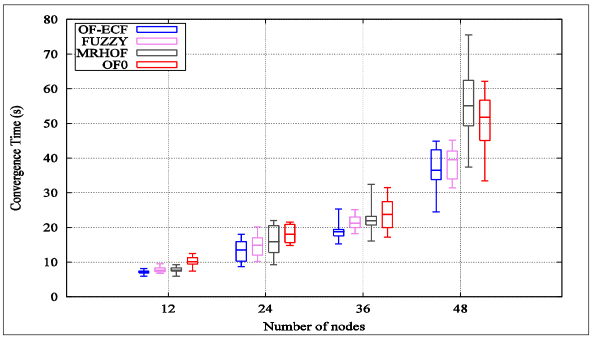

Figure 1: Convergence time in function of the number of nodes.

We notice that the convergence time linearly increases with the increase of the number of nodes in the DAG. The figure reveals that our proposed objective function and the FUZZY objective function always converge faster for all the simulations compared to MRHOF and OF0. The MRHOF with ETX and OF0 have almost an equal convergence time when the network is small (12, 24 and 36 nodes). However, when the network density increases, the MRHOF has a significant increase in terms of convergence time. OF0 in large networks performs better than MRHOF but still worse than OF-ECF. OF-ECF and FUZZY objective function have similar convergence time variation while they use the same primary metrics. To sum up, our proposed objective function outperforms the standard OFs in terms of convergence time and slowly decrease compared to the FUZZY objective function.

2) Stability of the network

To record the network stability, we have calculated the overhead considering the four OFs. Figure 2 shows the transmitted routing control messages in the network using RPL for the objective functions: OF-ECF, FUZZY, MRHOF, and OF0. We notice that the use of OF-ECF has induced more overhead compared to the three other objective functions. Indeed, when a node changes its parents, it resets the Trickle Timer [23] and generates DAO messages, which leads to an increase of the overhead. It is worth noting that nodes must transmit more messages to check the availability of candidate neighbours to choose the best parent from them. Thus, calculating the best value of the composite metrics resulted in more control messages in the network. In contrast, MRHOF and OF0 do not take into consideration the optimization of the parent selection process, which explains the low traffic overhead. Concerning the FUZZY objective function, it produces less overhead compared MRHOF and OF-ECF because it does not send DAO messages while it selects the same best parent frequently. Although the OF-ECF provides more overhead than MRHOF and OF0, it improves the reliability of links and network lifetime as shown in the next figures.

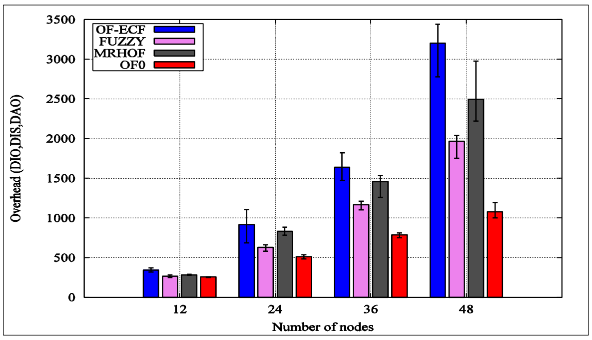

Figure 2: Comparison of the overhead versus the number of nodes.

3) Reliability of the network

To investigate network reliability, we measured the packet delivery ratio (PDR). Figure 3 exposes the study of the average variation of PDR value considering a network of 48 nodes during the simulations.

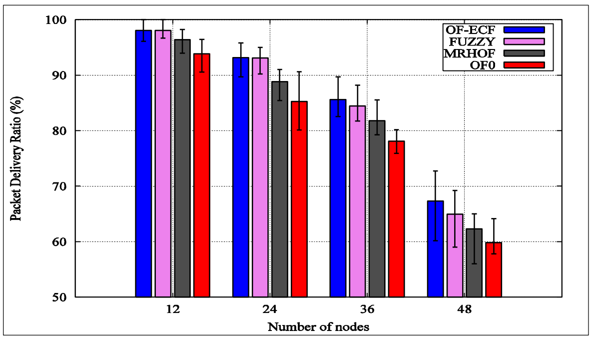

Figure 3: Comparison of the Packet Delivery Ration versus number of nodes.

According to the figure, the variation of PDR value of our OF outperforms the studied objective functions. At the beginning of the simulation, FUZZY takes the lead when the links are still good and then it finishes as the runner-up.

MRHOF finishes as the worst objective function, which is mainly due to its bad links choice during the last period of simulation. Selecting the same best parent continuously by many sensor nodes lead this preferred parent to drain its energy quickly. MRHOF has better PDR than OF0 because it calculates the best routes according to the ETX metric.

4) Lifetime

Measuring the operational time of the network is necessary for evaluating every routing protocol. We measured the lifetime of OF-ECF, FUZZY, MRHOF, and OF0 based networks versus the network size. Figure 4 demonstrates that in the case of the use of our objective function OF-ECF, the network lifetime has been extended compared to other objective functions. The integration of energy as one of the core metrics of OF-ECF and FUZZY was a good choice because it enhances RPL protocol and makes it an energy-aware protocol. Therefore, our composition method is quite light compared to the fuzzy logic method, which is a heavy objective function in terms of calculations. The calculations are made using the fuzzy logic method resulted in an increasing amount of energy consumption. Moreover, our strategy of selecting the preferred parent balances the energy consumption between nodes and it delays the battery depletion of the first nodes.

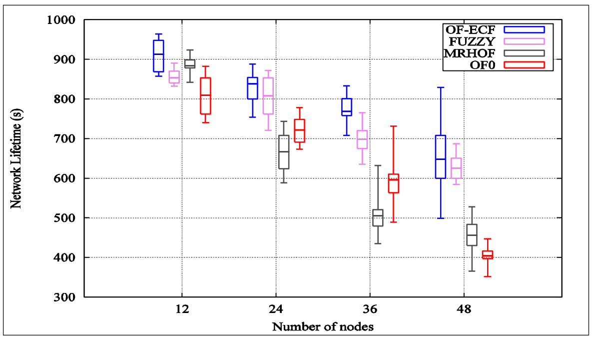

Figure 4: Comparison of the lifetime of provided by the OFs versus the number of nodes.

In terms of extending the network lifetime, OF-ECF has impressive results compared to the FUZZY objective function, OF0, and MRHOF with ETX. Its scheme distributes energy consumption in a balanced manner. We obtained 30% extended lifetime compared to the previous standard version. The next subsection studies energy consumption and its distribution among the nodes.

5) Measurement of energy consumption

Energy consumption is a critical parameter for a successful sensor network operation since the sensor nodes are battery powered. For this reason, we measured these metrics to extrapolate its impact on network performances. As shown in Figure 5, OF0 consumes less energy than OF-ECF and MRHOF with ETX. Although this objective function does not deplete a large amount of energy, it still performs poorly in terms of QoS. MRHOF with ETX focus on selecting good links, and it does not consider the probability of selecting expensive links in terms of energy. Compared to MRHOF, FUZZY and our proposed objective function have a less increase in energy consumption due to calculations of the best parent among candidate nodes and the generated traffic. FUZZY objective function does more calculations while selecting the preferred parent and this is the reason why it depletes more energy than our proposed solution. Moreover, OF-ECF balances the energy consumption to increase the network lifetime and the nodes able to keep their energy for a long time.

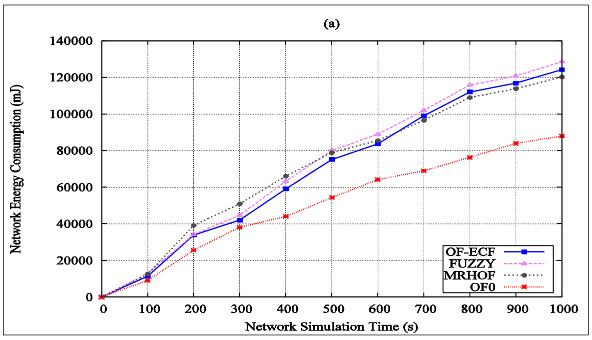

Figure 5: Total energy consumption of network and Energy consumption distribution.

VI. CONCLUSION

In this paper, we proposed an enhancement of the RPL routing protocol based on its objective function. Our new approach called OF-ECF combines three main metrics namely ETX, Consumed Energy and Forwarding Delay to overcome the single metric limitations. The new composite metric has been used to select the preferred parent among candidate parents to forward a data message. The combination of metrics used the additive metric composition based on a weight parameter that identifies the power of each composing metric. Compared to other available objective functions FUZZY, OF0 and MRHOF, the simulation results showed that our proposed solution outperforms the other algorithms in terms of network lifetime of the reliability. In future work, we will try to implement this enhanced routing scheme in a heterogeneous wireless sensor network where many applications can be deployed.

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