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Energy Consumption Management in IoT by Load Balancing at Near-Root Nodes in RPL Protocol

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ABSTRACT: Managing energy consumption in Internet of Things constitutes a challenge for researchers. Many existing works address this question. Some approaches propose solutions based on artificial intelligence. Other studies are based on improving existing routing protocols. The results obtained are promising and the energy gains recorded are remarkable. However, the majority of works in the literature propose a global optimization approach in the network to manage traffic flow. In doing so, we are led to neglect the bottlenecks especially around the convergence point. The objective of this work is to propose an improvement of RPL protocol, a popular routing protocol in Internet of Things.

KEYWORDS: Internet of Things, energy consumption, network load, RPL

I. INTRODUCTION

The technological revolution of the last ten years revolves around the Internet of Things (IoT). Despite its multiple applications, IoT leads to increase energy consumption. This becomes a major challenge for researchers. Indeed, IoT networks are subject to resource constraints such as low processing capacity, limited bandwidth and rapid battery wear [1].

Many works address this question. It is addressed from several angles, including artificial intelligence and improvement of existing network protocols [2]. RPL routing protocol is emerging as a promising routing solution in IoT. This protocol requires the presence of a so-called convergence node also called root. The good performance of the network depends on the good performance of the convergence node and its neighbors. Few efforts have focused on the problem of load balancing on nodes close to the convergence point in IoT.

The question that emerges is how to design efficient load balancing mechanisms in the RPL protocol to optimize the performance of IoT networks, especially for nodes close to the root.

This paper proposes a contribution aimed at improving the energy efficiency of the RPL network, in particular to avoid premature exhaustion of nodes close to the root. A load balancing algorithm, E-COM-OF (Enhance Combined Metric Objective Function), is proposed. It is based on a distribution of nodes into three zones with the independent application of the objective functions COM-OF (Combined Metric Objective Function) and MRHOF (Minimum Rank with Hysteresis Objective Function). The rest of the paper includes the presentation of RPL routing protocol, a review of the state of the art, the proposed approach, the performance evaluation which sets out the results recorded and the limits of the work.

II. RPL PROTOCOL

Research on routing protocols suitable for low-power and lossy networks (LLN) emerged with the proliferation of mobile wireless devices in the 2000s. Initially designed for networks of mobile nodes without energy constraints, MANET protocols [3] evolved into LLNs [4], dedicated to economical and constrained devices, leading to the creation of the ROLL working group at the IETF to standardize the RPL routing protocol in 2008 [3].

A. Characteristics of RPL protocol

RPL protocol is suitable for 6LoWPAN [5] Internet of Things networks. It establishes a dynamic topology to route IPv6 datagrams between sensor nodes avoiding loops and taking into account quality of service. Each intermediate node acts as an IP router. It brings together the fragments and analyzes the destination address to direct the packet to the transport layer or another sensor node. As mentioned in[6], RPL is also a proactive protocol and based on a distance vector algorithm which ensures efficiency with minimal resources and allows it to generate routing tables without requiring a global view of the network.

B. Control messages in RPL

Data routing with RPL protocol uses a graph. During the graph construction, nodes exchange DIO (DODAG Information Object), DIS (DODAG Information Solicitation), DAO (Destination Advertisement Object), and DAO-ACK (Destination Advertisement Object ACKnowledgement) messages. The 6BR (root) initiates the process by broadcasting the DIO message, prompting neighboring sensor nodes to decide whether to join the graph based on the objective function and cost of the announced path [6]. Once integrated, a node automatically has a path to the root and, if it acts as a router, broadcasts its local knowledge about the graph to its neighbours.

C. Topology buildingt

DODAG (Directed Acyclic Graphs) graph is a cycle-free directed graph structure used to organize and optimize communication in IoT networks. It defines the hierarchy and relationships between nodes, facilitating efficient and energy-efficient routing in low-power networks. The construction of DODAG (Directed Acyclic Graphs) relies on the Neighbor Discovery (ND) process, which includes broadcasting DIO control messages to establish ascending routes and broadcasting DAO messages to creating descending routes. The DODAG root initiates this process by broadcasting a DIO message, thus revealing its DODAGID and its objective function. Client nodes respond by adding the DIO transmitter to their parent list and then calculate their own rank. Finally, they transmit the updated DIO message. A client node then chooses its preferred parent to direct upward traffic.

A node affiliated with a DODAG that receives another DIO message can reject it, process it to maintain its rank, or improve its rank according to the criteria specified by RPL.

D. Concept of Objective Function in RPL

The objective function (FO) in RPL protocol is detailed in [7]. It plays a crucial role in the construction of the DODAG graph. An objective function can serve as a criterion for the choice of parents of a node and the creation of routes. When receiving DIO messages broadcast by the DODAG root, the nodes calculate their rank with an objective function. The latter ensures a hierarchy of network nodes which promotes the selection of appropriate parents and optimizes routing paths by considering various parameters such as quality of service, energy consumption, and other metrics specific to the Internet of Things context.

There are two Objective Functions used in RPL protocol: Objective Function Zero (OF0)[8]and Minimum Rank with Hysteresis Objective Function (MRHOF)[9].

1) Objective Function Zero (OF0):

***Calculation of rank* in *OF0*:** A The objective function Zero (OF0) calculates the rank of a node *i* relative to a parent *j* with equation (1).

$$Ri = Rj + increase\_rank(\mathrm{i,j}) \qquad (1)$$

Where Rj represents the rank of parent *j*, and increase_rank, the expression of the quality of connectivity between node *i* and node j as defined in equation (2).

$$increase\_rank(\mathrm{i,j}) = (Rf\ x\ Sp\ x\ Sr)\ x\ MinHopRankIncrease \quad (2)$$

where Sp (step of rank) is the expression of the quality of connectivity towards the node P used to calculate its rank. It is a normalized value between 1 (very good) and 9 (very bad)

Rf (rank factor) is used to increase the importance of quality. Default value of Rf is 1.

Sr is the stretch of rank. By default, it’s set to 0 and can take a maximum value of 5.

MinHopRankIncrease specifies the minimum rank difference that must exist between a node and its potential parents during the parent selection process. It is set to 256 by default.

***Parent selections in OF0*:** In addition to calculating the rank of a node relative to another given node, the Objective Function additionally defines how to select a parent. Indeed, OF0 allows to select the preferred parent (the default route), and a backup parent based on the priority at the lower rank, the connectivity, the parent which offers connectivity to the most privileged root, the consideration of the recent version of DODAG, and the lowest rank for the node.

2) Minimum Rank with Hysteresis Objective Function(MRHOF):

Minimum Rank with Hysteresis Objective Function(MRHOF) aims to optimize route according to a metric, but avoiding too frequent path variations due to a minimal change in metric. For this, MRHOF introduces a hysteresis function. It only works with additive metrics along a route, and the metric is disseminated by the DIO message using the DODAG metric container option.

***Rank calculation in MRHOF*:** The calculation of rank of a node *i* relative to a parent *j* in MRHOF is defined by equation (3):

$$Ri = FonctionMetric\ (pathCost) \qquad (3)$$

with

$$pathCost\ (i) = ParentPathCost(j) + linkCost \qquad (4)$$

Equation (3) shows that the pathCost is calculated as a function of the metric used.

The path cost pathCost(i) is obtained by summing the cost of the link a given parent *j* with the cost of the path announced by this parent ParentPathCost(j) according to equation (4).

***Selection of parents in MRHOF*:** In order to select a parent, MRHOF introduces a hysteresis function which can be expressed by the pseudo-code in Algorithm 1.

Let P1 and P2 be the respective path costs of a parent 1 and a parent 2.

P1 is the preferred parent and P2 a candidate parent.

Algorithm 1: Parent selection algorithm

```
If PathCost (P1) – PathCost (P2) > ParentThreshold
        Parent P2 becomes the preferred parent.
Otherwise
        P1 remains the preferred parent.
End if
```

ParentThreshold represents the hysteresis function, i.e. the minimum difference between the path cost of the preferred parent and the path cost of the candidate parent that triggers the selection of a new preferred parent.

III. STATE OF THE ART

The problem of energy management arises in RPL protocol in its basic operation. The timer algorithm, known as the "Trickle Timer" [10], is responsible for this mechanism, aiming to reduce the number of unnecessary control messages. However, various studies have demonstrated that this timer has drawbacks in dynamic environments, leading to inefficient data transmission and high energy loss due to packet delivery failures [10]. In order to increase the network lifetime, several energy-saving routing protocols have been proposed to meet the Quality of Service (QoS) requirements of IoT applications. The work in [11] fits precisely into this perspective, describing an intelligent mechanism for self-optimizing the energy consumption of IoT objects based on a fuzzy logic model. The results show an increase in node lifetime and intelligent control of object activation autonomously.

While recent research focuses on the cognitive management of energy consumption in IoT [12], the work in [13] addresses the problem at the level of radio spectrum management. It proposes OSCAR algorithm to minimize latency and energy consumption in the RPL network, improving the time slot allocation mechanism in 802.15.4e networks in TSCH mode. Although this approach significantly improves energy consumption, it leads to bottlenecks at nodes near the DODAG root under high activity.

Another perspective for optimizing energy consumption concerns balancing traffic loads in LLN networks. One of drawbacks of RPL protocol is the lack of load balancing support, leading to inequitable distribution of traffic in the network which can decrease network efficiency [14].

Authors of [15] propose an improvement based on RPL protocol which uses a combination of metrics to maximize the lifetime of nodes. Their objective function COM-OF is used in the selection of parents to manage the distribution of the load holistically. The results show relatively better performance compared to RPL's OF0 and MRHOF objective functions, with a decrease in overall energy consumption, an improvement in network lifetime, a reduction in the average number of child nodes per parent, and an improvement in packet delivery rate. However, managing load distribution across the entire network does not guarantee an optimal result around the DODAG root. Node overload persists at this level, so finding a solution is imperative.

IV. PROPOSED APPROACH

A. Load balancing in nodes near the DODAG root in RPL

Most research on traffic load balancing in RPL, as discussed in the state of the art, takes a holistic approach to load distribution across the entire network. Thus, during the parent selection process, the algorithm is applied to all nodes in the network, including those with negligible traffic load. This approach may result in unnecessary overconsumption of energy because some load balancing mechanisms require frequent communication between nodes, leading to additional energy consumption. Additionally, load balancing can introduce some latency into data transmission because nodes must make decisions based on the current network load. Finally, these mechanisms may require additional resources, such as increased computing and storage capacities on network nodes. We therefore support the idea of restricting the application of load balancing in RPL in order to achieve more interesting results in energy management.

In this study, our approach to optimize energy consumption in IoT is to propose a new objective function based on the COM-OF function to achieve load balancing during parent selection. The fundamental difference lies in the fact that this new function only operates on nodes close to the DODAG root, unlike standard approaches. The proposed algorithm is presented below.

B. E-COM-OF Algorithm of Entire Document

The objective function algorithm that we call "Enhance Combined Metric Objective Function" (E-COM-OF) is presented in Algorithm 2. The objective of this algorithm is to perform load balancing on nearby nodes of the DODAG root in order to solve the problems of overload and energy waste caused by excessive overexploitation of these nodes. From this perspective, the E-COM-OF algorithm adopts a targeted optimization approach, using a combination of node and link metrics to calculate the rank required to select parents close to the sink.

E-COM-OF is distinguished by a classification of nodes into three zones according to their rank value. So, all nodes with a rank lower than 256 belong to zone 0 and are considered to be closest to the DODAG root.

Zone 1 nodes are intermediate nodes. These are nodes with a rank between 256 and 512.

Finally, all nodes with a rank greater than 512 are in zone 2 and are identified as being furthest from the DODAG root.

When a node changes zones in the network topology, its rank changed and its zone ID is also changed, and the COM-OF objective function is applied only if it ends up in zone 0. In this case, during the construction of the DODAG, the DIO message includes the parent ID. When a node accepts the DIO message, it tracks the number of children by comparing IDs, and the traffic is evaluated by the throughput metric. The node's ELT (Expected Transmission Count) value, based on traffic, ETX and residual energy are used to calculate its new rank. The objective function selects a parent with few children, long life with low power consumption and reliable linking which contributes to load balancing in the near-root network.

Outside of this area, the node is no longer impacted by our load balancing solution and is then supported by the MRHOF objective function. In this configuration, the rank calculation considers the metric number of ETX transmissions and the selection of preferred parents involves the hysteresis function via the DIO message.

Tableau I: Notation used in the algorithm

CurrentNode(CN)	Current node
NodeID	ID of the current node
CC	Child Counter
ParentID	ID of the parentnode
ParentNodeID(PN)	ID of the potential parent node
ELTinv	Inverted ELT metric for rank calculation
ZoneID	ID of the zone

Algorithm 2: E-COM-OF objective function Algorithm

```
Zone_0     : Set of nodes belonging to zone 0 (nodes closest to the DODAG root).
Zone_1     : Set of nodes belonging to zone 1 (intermediate nodes).
Zone_2 : Set of nodes belonging to zone 2 (nodes farthest from the DODAG root).
CurrentNode (CN) : Node currently being processed.
NodeID : Identifier of the current node.
ParentNode (PN) : Potential parent node.
ParentID : Identifier of the parent node.
ChildCounter (CC) : Counter of child nodes for a parent.
ELTinv : Inverted ELT metric for rank calculation.

Begin
//Classification of nodes based on their rank for zones 0 to 2
//ZoneID increases with distance from the DODAG root a smaller value means closer proximity to the root
If Rank < 256 Then
    ZoneID ← 0
    Else If    Rank <= 512 Then
    ZoneID ← 1
    Else
    ZoneID ← 2
End If
—
Section 1: Load Balancing Algorithm Near the Root (RPL COM-OF Algorithm)

If ZoneID==0 Then
    The node is considered close to the DODAG root.
    CurrentNode←DIO
    If NodeID==ParentID Then
        ChildCounter←ChildCounter+1
    End If

//Rank calculation based on ELTinv and child node count
    For each node in Zone_0
    Calculate and update the ELTinv value and ChildCounter for each node in the zone.
    Calculate the rank of each node.
    If Rank of the sending node < Rank of the current node Then
        Add the sending node as the preferred parent.
        Destroy parent runs.
    Else
        Request local maintenance in the DODAG.
    End If
    End For
End If
—
Section 2: Parent Selection (Classical RPL MRHOF Algorithm)

If ZoneID >= 1 Then
    For each node in Zones 1 and 2
        Calculate the rank of each node.
        If Rank of the sending node < Rank of the current node Then
            Add the sending node as the preferred parent.
            Destroy parent runs.
        Else
            Request local maintenance in the DODAG.
        End If
    End For
End If
—

End
```

V. TOOLS AND METHODS

A. *Tools : The Contiki-Cooja simulator*

To study the performance of the E-COM-OF algorithm, we used some reference tools in this area. These are VMware virtualization software, Contiki OS Open Source operating system[16]and the Cooja simulator/emulator shown in Figure 3.

The physical computer used is equipped with an AMD Ryzen 7 PRO 5850U 1.90 GHz processor, 16 GB RAM memory.

B. *Methodology used*

Three routing scenarios were implemented. A scenario for a study based on 10 nodes, then 30 nodes and finally 50 nodes. This made it possible to evaluate the behavior of the objective function E-COM-OF in different conditions in relation to the desired optimization. The network topology is an area of 100m × 100m for 10, 30 and 50 nodes. The DODAG root being located at the upper right corner of the simulation area. All nodes are launched with a full battery, set at 880mAh of charge representing 100% energy over a duration of 60 minutes. The details of the parameters are recorded in Table 1. The root node is created from the rpl-udp-powertrace.csc file contained in the rpl-udp directory of the Contiki simulator. The topology nodes that exchange data towards the root are also implemented from the rpl-udp-powertrace.csc file located in the rpl-udp directory. Packet exchanges between nodes are managed by the system according to the random arrangement of the nodes in the topology.

C. Evaluation criteria

We evaluate the performance of our proposed E-COM-OF objective function in terms of packet delivered rate (PDR) and energy consumption in the network which we compare with the results of the benchmark COM-OF objective function.

D. Implementation and simulation

1) Simulation details:

Tableau II: Notation used in the algorithm

Settings	Values
Network simulator	COOJA under Contiki OS (2.7)
Radio environment	Unit disk graph medium (UDGM)
Node type	T Mote Sky
Network area	100m×100m
ELTinv	Inverted ELT metric for rank calculation
Number of nodes	10, 30, 50
Number of root nodes	1
Transmission range	100m
Total frame size	127 bytes
Data packet size	50, 100) bytes
Simulation duration	60 mins

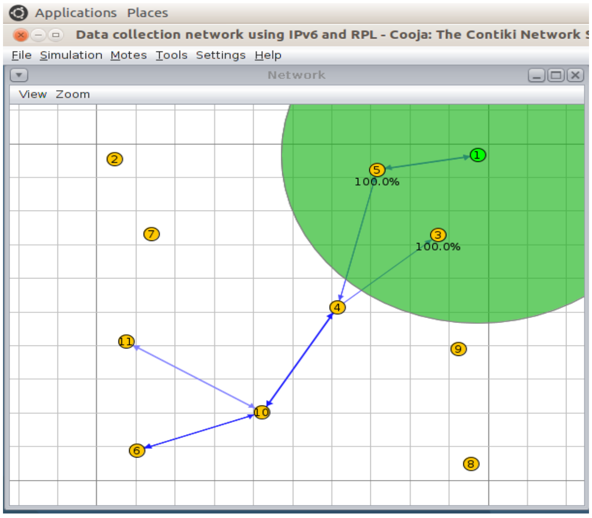

Figure 1 View of the simulation under Contiki-Cooja

2) Simulation details:

To perform the simulations, we consider parameters such as the number of child nodes (ELT), the estimated lifetime of the nodes, the number of transmissions (ETX) and the residual energy of the nodes located in the area adjacent to the sink (zone 0).

VI. RESULTS

A. Simulation scenario 1: 10 node case

Figure 2 reveals that the energy consumption of nodes increases with time. An identical energy consumption of the nodes that use the COM-OF and E-COM-OF objective functions up to 20 min is also observed. But from 40 min, energy consumption with E-COM-OF drops by around 10%.

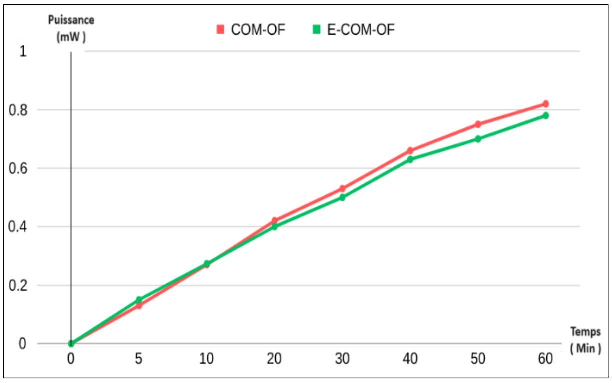

Figure 2 Power consumption for 10 nodes

B. Simulation scenario 2: 30 node case

In Figure 3, we note as in the previous scenario that the energy consumption of the nodes increases with time and it remains the same up to 30 min for the two Objective functions COM-OF and E-COM-OF. However, from 30 min onwards, energy consumption with E-COM-OF drops by around 10% on average.

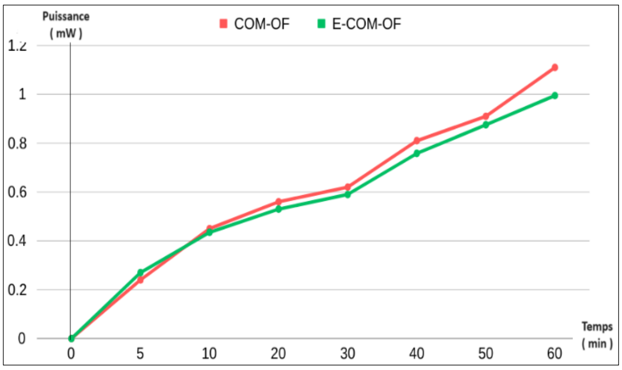

Figure 3 Power consumption for 30 nodes

C. Simulation scenario 3: 50 node case

The curves in Figure 6 exhibit identical energy consumption at nodes that use COM-OF and E-COM-OF up to 10 min. The difference occurs beyond 10 min with a drop of around 15% on average compared to nodes that use the COM-OF function.

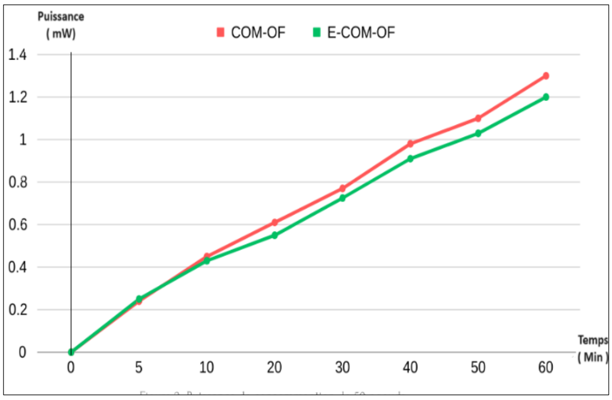

Figure 4 Power consumption for 50 nodes

D. Packet delivery rate in the network

Figure 5 shows that in small networks, E-COM-OF and COM-OF show the same packet delivery rate. For medium-sized networks, E-COM-OF can increase the packet delivery rate by 2%, with a maximum value of 98% compared to COM-OF.

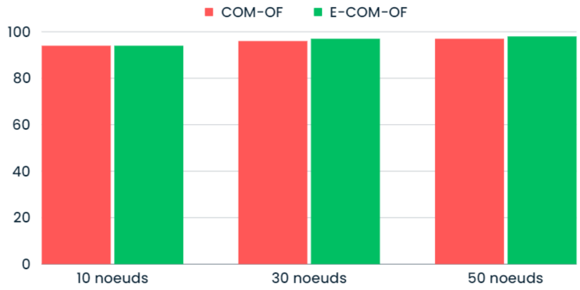

Figure 5.Packet delivery ratio (PDR) comparison

VII. DISCUSSION OF RESULTS

This study highlights the critical importance of traffic load balancing in near-root nodes in RPL to improve network performance. The results suggest that fair distribution of traffic in these nodes promotes more efficient use of resources and helps reduce overloads on certain nodes in the network. This is in line with the work [18], which focuses on recent developments in the objective functions of the RPL protocol in the context of IoT applications. Data analysis shows that applying specific load balancing strategies in the RPL protocol can significantly enhance network stability and responsiveness. Although the study has limitations, such as security in IoT networks [19], the restricted scope of the simulated scenarios, it nevertheless highlights the importance of integrating load balancing into the design of routing protocols like RPL, thus paving the way for networks more efficient and resilient.

CONCLUSIONS

At the end of this work, we conclude that the study carried out highlights the crucial importance of load balancing in the nodes close to the root of the RPL protocol. This helps improve the efficiency and stability of IoT networks. The obtained results indicate that equitable traffic distribution optimizes resource utilization, reduces overloads and enhances network reliability.

Looking ahead, it is recommended to deepen our approach in complex deployment scenarios, focusing on dynamic adaptability [20] and synergies with other advanced research, to create more robust IoT networks in the face of evolving challenges.

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