A survey on enhancements of routing protocol for low power and lossy networks: focusing on objective functions

Ditixa Vyas, Ritesh Patel
U & P U Patel Department of Computer Engineering, Faculty of Technology and Engineering, Charusat University, Anand, India

Article Info

Article history:

Received Jun 2, 2024
Revised Dec 26, 2024
Accepted Jan 14, 2025

Keywords:

Internet of things
Low power wireless network
Mobile network
Objective function
Routing protocol for low power and lossy network

ABSTRACT

People live in the age of smart devices. The concept of the internet of things (IoT) needs to be brought up whenever smart gadgets are shown. Furthermore, every gadget is gradually turning into a mobile node. These devices are utilized in low power and lossy networks because of their characteristics. Numerous obstacles exist in this field, motivating academics to focus on routing, connections, data transfer, and communications between nodes. In relation to this, the internet engineering task force (IETF) group already created a routing protocol for low power and lossy network (RPL), which was suggested for static networks and has since undergone numerous improvements. This article introduces the low power wireless network (LPWN) with a detailed model of the RPL protocol. It has also been considered how the destination-oriented directed acyclic graph (DODAG) is formed, and control messages are used to communicate between nodes in the RPL. The objective function (OF) is the center of the RPL. The principal objective functions objective function zero (OF0) and minimum rank with hysteresis objective function (MRHOF), which IETF group suggested, cannot function in the existing mobile network due to node disconnection and intermittent connectivity. The authors have enumerated and briefly discussed numerous RPL enhancements with new OFs. Numerous problems that the RPL routing protocol faced with mobility have been resolved.

Corresponding Author:

Ditixa Vyas
U & P U Patel Department of Computer Engineering, Faculty of Technology and Engineering, Charusat University
Anand, India
Email: ditixamehta@gmail.com

1. INTRODUCTION

The internet of things (IoT) is considered important for the coming generation. Connecting all heterogeneous devices-which includes small and ideal gadgets as well-to the internet is the fundamental aim of the IoT. Due to the fact that IoT applications like smart homes, smart cities, and healthcare monitoring require low-power and inexpensive equipment, Wi-Fi nature and environmental context are used in these applications. There are a number of problems with IP packet routing in the IoT space. To overcome this, the 6LoWPAN protocol was created, which uses an adaption layer to enable IPv6 communication across IEEE 802.15.4 networks. Subsequently, the internet engineering task force (IETF) created routing protocol for low power and lossy network (RPL), a routing protocol used for low-power and lossy networks, to help limited devices connect to the internet. But because the standard RPL specification is so complicated, there is still room for more study and improvement in this field.

An IoT tool combines a variety of sensor devices with a wireless networking component. The sensor device is in charge of gathering data, and depending on what the IoT applications require, the wireless module has exclusive radio range and transmission power. Due to the fact that many IoT equipment may run on batteries, the radio technologies used by these devices have limitations in terms of broadcast range and power consumption. The IoT employs the hop-by-hope approach. Multihop communication in wireless networks causes packet loss and consumes a lot of energy, which delays grid processing. Many IoT applications in use today require multi-hop communication in order to interact with both stationary and mobile devices in the network. A strong routing protocol is therefore necessary in this type of environment due to frequent topology changes, node mobility, and hop-by-hop communication.

An effective routing protocol is crucial for low power lossy network (LLN) because it must be able to quickly identify mobility, which could reduce packet loss due to device movement and reduce the consequences of discontinuance. The IETF's RPL protocol was first limited to use in static LLN network topologies. Consequently, it encounters several problems, such as low packet delivery rate (PDR), when utilized in mobile topologies. RPL has been improved upon by other researchers, which is why mobile situations can also use it. Some of the RPL issues are linked to a lack of mobility tool identification and an inefficient method for choosing the preferred parent while taking mobility into account.

Mobility has proven to be a major hurdle and a barrier for the research community in the IoT area, especially in the context of low power wireless networks (LPWNs). Many kinds of protocols and standards have been proposed over the last few decades to help in the adoption of LPWNs. The purpose of this paper is to review some of these standards and the processes that go along with them, and to look at several works that deal with multiple RPL objective functions.

The main routing protocol, known as RPL, is the same for routing in lossy and low-power networks. However, compared to its performance, researchers have conducted a great deal of research. From this point forward, evaluating and considering how the RPL behaves in several contexts and settings is essential to distinguishing its requirements and limitations, which enables it to be improved even further.

The remaining part of this article is organized as follows: In section 2, motivation of carrying this research work is mentioned, in section 3 the background and related work of the RPL protocol, its issues and limitations in the mobile network is discussed. In section 4 the relevant work related to proposed enhancement of the RPL objective functions are discussed in different ways. The mobility impact is still a vast research area in RPL protocol is mentioned in section 5. Finally, section 6 concludes the paper.

2. MOTIVATION

As was previously noted, RPL was first developed for networks with static topologies. But in many IoT utility application contexts these days, mobility enablement is a must. The network topology has movable nodes, which causes numerous performance problems. Mobility gives rise to a problem with packet loss and frequent stops. RPL, however, can be modified to provide better mobility assistance. Additionally, as we manage node mobility, we evaluate RPL boundaries and the different improvements that will be made in the future literature to improve mobility support in RPL.

3. BACKGROUND

3.1. Low power and lossy networks

3.1.1. LLN characteristics

These networks, whether wired or wireless, with all sorts of that really make you wonder they function. For starters, we're talking about limited supply, processing abilities, and storage space. These networks have some funky features like slow data speeds, one-way links, lots of data disappearing into thin air, and data rates that change on a whim. Plus, they cannot communicate over long distances compared to your regular network setup. You can think of LLNs as a mix between a couple of routers hanging out together or tons of tiny gadgets running on minimal juice and struggling to find their way around. All these devices trying to get in touch with the vast Internet world through a special gatekeeper known as an LLN border router (LBR). That fancy router is not fazed by any resource. But if you peek inside these networks, you will notice that most hosts share similar qualities-except for a few rebel gadgets with their own ideas about computing power or memory storage. This whole system by the IETF that sorts sensor nodes into three different classes:

a. Class 0 is like those forgetful gadgets who need someone else to do all the talking for them because let's be real-their memory is not winning any awards anytime soon!
b. Class 1 devices possess relatively more resources, enabling independent communication with other hosts.
c. Class 2 devices have the least constraints, supporting protocol stacks akin to traditional computers [1].
d. Despite these differences, all classes benefit from lightweight protocol stacks, optimizing application resources, reducing development costs, and facilitating interoperability.

The primary router in the network structure establishes an Internet connection with a local server, as shown in Figure 1. Sink routers connect to the primary router and function as LLN border routers. The mobile network's entrance is provided by LLN border routers. The LPWN display physical access points (APs). Using connection metrics, mobile nodes in LPWN can establish a connection with any AP. These APs, also known as mobile nodes (MNs), are embedded communication devices that come with power sources, transceivers, and microprocessors. They can represent a variety of sensor nodes. Every node is capable of sensing, processing, and retrieving network data. Typical IoT devices are able to sense a wide range of factors, including light levels, high temperatures, power line voltage signals, and physiological data like oxygen and heart rate. These gadgets stand out for being reasonably priced, lightweight, and small.

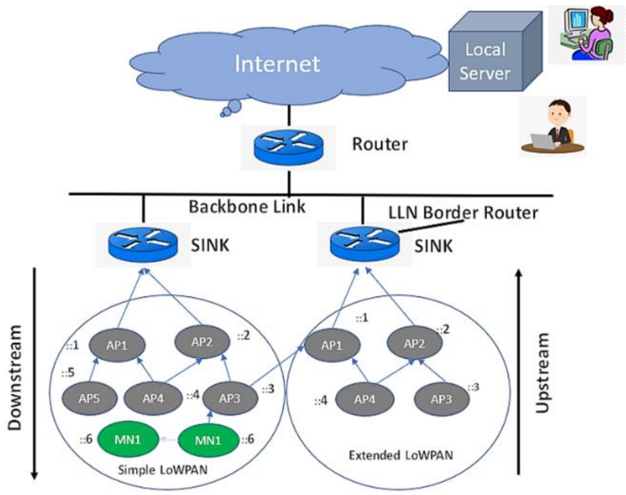

Figure 1. Low power lossy network

3.1.2. LLN standards technologies

Various radio technologies and standards have been developed to help ease the deployment of LLN in the IoT. Some of these include the 6TiSCH and IEEE 802.15.4 standards, which address various MAC and physical layer issues. In addition, the 6 LoWPAN standard can be used to bridge the 3rd and 4th protocols, such as RPL and IPv6.

a. IEEE 802.15.4 (layers 1 and 2)

It is got two physical layers that can work in different frequency bands. Then, there's the Media Control layer, meant to keep the network activities in check simply and efficiently. Over the years, there were quite a few revisions and tweaks to the standard [2]. Big ones happened in 2006, 2007, and 2009. All these adjustments got rolled into one neat package by 2011 [3]. IEEE 802.15.4 tops out at 250 kb/s for transmission rate [2]. The MTU is set at 127 bytes, but only about 116 bytes are available for upper-layer protocols [4]. The MAC layer does its job using a sense multiple access with collision avoidance (CSMA/CA) setup to ensure a smooth ride on that wireless channel [4].

b. 6LoWPAN (layer 2.5)

Use application gateways to change the non-IP format these networks liked into the IP world. Maybe IPv6 could actually work for LLNs after all? Nowadays, LLNs are like MVPs in the world of IoT [5]. We're talking about having smartphones, computers, actuators, sensors - you name it - all playing nice together on the Internet without any isolation issues from those old-school solutions [6], [7]. Concerns about device needs and communication tech did not magically disappear when LLNs switched over to IPv6 [8] land. For instance, IEEE 802.15.4 standard on layer 2 with its wimpy 127 bytes limit trying to play nice with IPv6's chunky 1280 bytes requirement on layer 3 - talk about mismatched things [9]. Good thing heroes from "IPv6 over low power wireless personal area network" squad at IETF stepped in to save the day. They built this adaption layer connecting layers 2 and 3 [10]. To keep those IP datagrams flowing smoothly in those IEEE frames, these geniuses at IETF cooked up wicked tricks like compressing IPv6 headers, chopping packets into bite-sized pieces (fragmentation), and stitching them back together again (reassembly) [11].

c. IEEE 802.15.4e TSCH and IETF 6TiSCH (layer 2)

IEEE 802.15.4e TSCH and IETF 6TiSCH (layer 2) protocols. Back in 2012 [12], the IEEE came up with the time-slotted channel hopping (TSCH) to make multi-hop networks more stable. They wanted to tackle the issues with unpredictability and resource limits in existing systems. The TSCH mode brought together channel hopping and TDMA [12], [13] to make things more reliable and energy efficient. Channel hopping helps networks stay strong, even when the channels are acting up. On the other hand, TDMA scheduling reduces conflicts and makes energy use smarter. It is like they are the dynamic duo of the network world! Then, the IETF stepped in with the “IPv6 over the TSCH mode of IEEE 802.15.4e” (6TiSCH) working group [14], [15]. To smoothly blend the TSCH MAC protocol into IPv6 LLNs, with a focus on industrial setups. This group introduced the 6TiSCH operation sublayer (6top), which handles resource management and how nodes chat with each other. As of now, 6TiSCH is still doing its thing, churning out RFCs and internet-drafts to keep things running smoothly. It is like a behind-the-scenes hero in the world of network protocols, making sure everything stays connected and efficient. As a result of IEEE and IETF's cooperative standardization efforts, the 6TiSCH stack-which is depicted in Figure 2(a) is a modified version of the 6LoWPAN stack which works with IPv6 communication over low-power wireless network shown in Figure 2(b). But the 6TiSCH adds the specific time slotted channel hopping (TSCH) mechanism.

IETF CoAP			**IETF CoAP**	
UDP			**UDP**	
IPv6	**IETF RPL**		**IPv6**	**IETF RPL**
IETF 6LoWPAN			**IETF 6LoWPAN**	
IETF 6TOP			**IEEE 802.15.4 MAC**	
IEEE 802.15.4e TSCH				
IEEE 802.15.4 PHY			**IEEE 802.15.4 PHY**	
(a)			(b)	

Figure 2. IETF protocol stack (a) 6TiSCH stack and (b) 6LoWPAN stack

3.1.3. Unique routing challenges in LLNs

Developing effective routing protocols for LLNs is influenced by their distinctive traits. These networks pose challenges due to constrained memory and processing resources, low data rates, limited power supply in most devices, and the lossy nature of interconnects. In the following discussion, we will explore some of the design challenges encountered in routing processes within LLNs.

It is projected that LLNs will be used for a variety of purposes, including industrial processes, environmental monitoring, home and building automation, military uses, and more. These many applications each have unique features [16], [17], which means that different criteria apply in terms of power consumption, latency, traffic overhead, reliability, and other performance metrics. Thus, striking a balance between these many, often incompatible requirements while staying inside the bounds of the application's resources presents a substantial problem for an LLN routing protocol [17].

a. Communication patterns

Multipoint-to-point (MP2P) communication is the main pattern seen in LLN applications [18]. In this arrangement, data is collected by a group of sensors and sent to a shared location called the sink or LBR. There are additional communication patterns as well, like point-to-point (P2P), in which a sensor node communicates with another node in the network, and point-to-multipoint (P2MP), in which the sink sends data to related sensor nodes [19], [20]. Another difficulty in designing LLN routing protocols is the variety of communication patterns.

b. Reporting model

These models come in all shapes and sizes, but mainly fall into three categories: query-based, event-based, and time-based.

- In the query-based model, data gets sent out only when someone explicitly asks for it. It is like waiting for a signal before sharing information.
- The time-based model where sensing devices chime in with their data at specific regular intervals. It is like clockwork-predictable and reliable.
- The event-based model where sensors holler out readings only when they detect sudden changes. It is like reacting instantly to surprises.

Sometimes these models get mixed up together like a blend of flavors. Sounds complex but can be quite effective. Routing protocols play a crucial role here-imagine handling messages efficiently while also conserving power. The bottom line is that how data moves around impacts everything from stability to energy use. It is like figuring out the best route on a map-precision and efficiency are key players here.

c. Scalability

LLNs are expected to operate across a spectrum of deployment densities, spanning from a few neighbors per node to potentially hundreds [19]–[41]. Therefore, a protocol must possess the flexibility to accommodate this wide range of scenarios, dynamically adjusting its parameters based on real-world conditions [17]. In essence, scalability becomes a crucial design consideration for an LLN protocol.

d. Scarcity of resources

The constrained resources within LLNs introduce a distinct set of challenges when devising efficient routing protocols and primitives. Primarily, the limited battery capacity of sensor nodes emerges as the most critical constraint and necessitates careful consideration [21]. Consequently, a routing protocol should aim to transmit only essential updates to maintain route freshness while conserving power effectively. Determining the appropriate frequency of updates-from periodic transmissions every second to bulk transmissions every few minutes-depends on the network's prevailing conditions and the specific application requirements, ensuring alignment with the application's energy budget [17].

e. Links unreliability

In LLNs, links are prone to loss and unreliability, meaning that an update may not reliably reach its destination upon initial transmission [22], [23]. Predicting the exact link loss rate beforehand can be challenging, with factors like receiver collisions, hidden terminal issues, and interference contributing to variable loss rates over time [22]. However, in certain instances, an estimated loss rate can be derived based on past deployments. Consequently, routing protocols need to efficiently function under such uncertain conditions.

f. Regarding mobility and network dynamics

While sensor nodes in LLNs are typically stationary, scenarios with a significant number of mobile nodes do exist [19], [20], [24], [25]. For example, in health monitoring applications, nodes are often mobile, as sensors attached to individuals monitor health remotely during their daily activities [26], [27]. Therefore, routing strategies must account for potential node mobility. With the advent of 6LoWPAN, there arose a demand for further IPv6-based routing solutions tailored to LLNs. Consequently, the IETF swiftly tasked the routing over low power and lossy networks (ROLL) working group with the design of such routing solutions [19].

3.2. RPL-routing protocol for low power and lossy network

Routing protocol for low-power and lossy wireless networks (LPWNs) that works on the IPv6 platform. The ROLL team at the IETF came up with it. It is kind of like a vector routing protocol but on top of the IEEE 802.15.4 data link physical layers. They use this funky thing called a destination-oriented directed acyclic graph (DODAG) to organize the nodes. Each router can figure out its parent nodes, which basically show the next step towards the DODAG root. By considering metrics or limitations among other potential choices. In the grand scheme of things, the lowest rank number, like in Figure 3, points to the shortest path to the root node. That is how they make the parent decision. RPL is versatile too-it can handle different types of communication like point-to-point, point-to-multipoint, and multipoint-to-point traffic. Every network with RPL has routers, hosts, and those low-power and lossy network border routers (LBRs). RPL sets up bidirectional links so that traffic can flow both ways-uphill and downhill.

When RPL gets into action, it is all about creating a network that looks like a tree. Just picture the border router (LBR) as the boss at the top of this tree structure. Then, connections are made between different players-hosts and routers. In this RPL world, every little node is given a rank. It is like ranking them based on how close far they are from the LBR. The LBR holds the prestigious title of having a rank value of zero. The DODAG leaf nodes ranks go up as you move towards them in the tree-like setup. Think of it as climbing up branches. All is done through something called routing metrics represented by those rank values. And these values are cooked up using an objective function (OF).

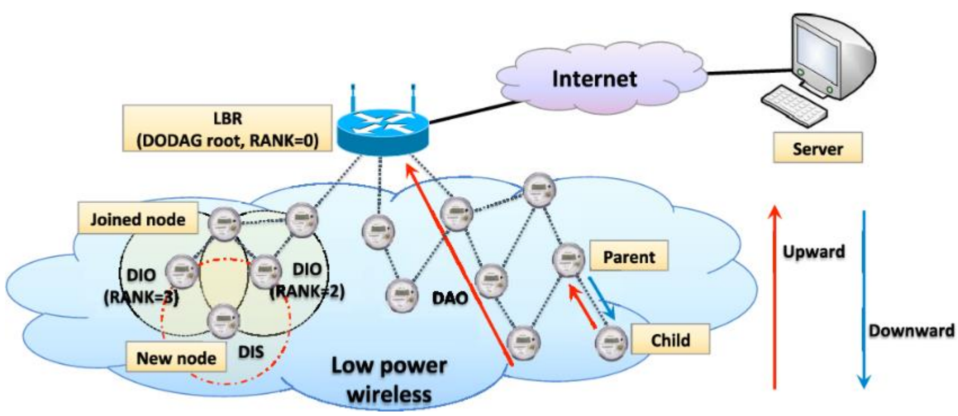

Figure 3. RPL with a single DODAG [28]

Certain protocols are used during parent selection in order to communicate with the parent and manage messages in the network. While the Trickle method uses DIO to create routes upstream in the DODAG, the neighbor discovery (ND), it is all about checking if our devices can reach their parents and sending out that crucial control info. This distributed information object (DIO) is like the messenger carrying key details about the network setup.

– The RPL instance ID: A special code telling us which networks are working towards the same goal. And then there the DODAG ID pinpointing that main boss of the network.
– DODAG version number: Keeps track of every change happening behind the scenes.
– Rank of each node: This number tells us where they stand in relation to their boss node. When things need fixing or setting up in a network world, internet control message protocol version 6 (ICMPv6) swoops in with its messages. These messages hold all sorts of juicy details about neighbors, routes, and paths - everything needed to keep our digital world running smoothly.

Four distinct types of control messages are used by the RPL protocol to communicate data and maintain topology.

– DODAG information object (DIO): DIO control messages containing the RPL instance are sent downward by the node that can act as a root or parent node. This makes it easier for other sensor nodes to integrate into the network and gives them access to the root node's IPv6 address, the current RPL instance, and the node's current rank.
– Destination advertisement object (DAO): The leaf node submits a DAO request to become a child member of the DODAG after receiving a DIO message from either the root node or a parent node.
– DODAG information solicitation (DIS): If a leaf node fails to detect any announcements, it can initiate a request message termed DIS. This neighbor discovery process involves the leaf node sending a request to the DIO message in order to identify neighboring nodes [6].
– DAO-ACK: It is a reply to a DAO message, transmitted by the root or parent node to the leaf to permit it to become a part of the current DODAG.

Three types of nodes are there in the RPL topology or network.

– Root nodes: The network node that provides connectivity to the leaf nodes is referred to as the gateway node.
– Router: These routers, in addition to the root node, are utilized to transmit topology and routing table data to neighboring nodes [29].
– Leaf (child) node: It cannot transmit DIO messages and can only become a member of the DODAG upon receiving a positive acknowledgement.

Control messages are transmitted at regular intervals in almost all routing systems, as Figure 4 shows. Devices may run out of energy as a result of this constant broadcasting, particularly in times of stability. The RPL protocol uses the Trickle algorithm to control the rate at which DIO messages are transmitted from the root node or parent nodes in order to mitigate this problem. When there are frequent changes to the network architecture, these control messages are sent more frequently.

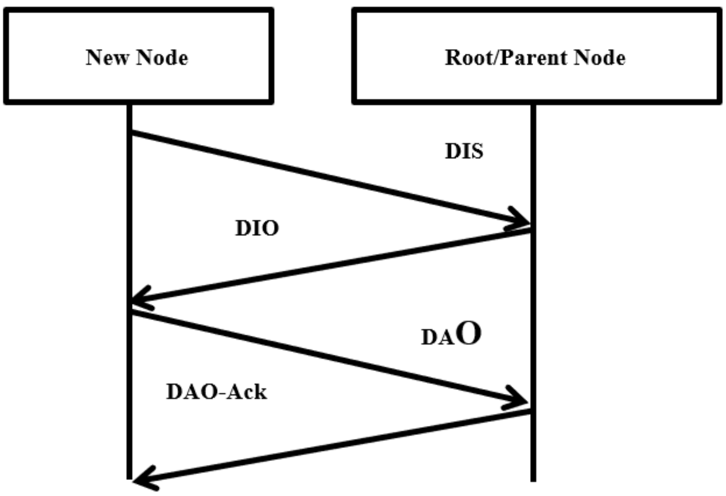

Figure 4. Control messages for RPL protocol

RPL includes an objective function (OF) module that nodes use as a measure to build or optimize a network. Based on this OF and depending on the rank value, RPL creates a DODAG in Contiki OS that includes path metrics, node policies, and loop-prevention rules. Using a metric customized for the application, the OF finds the best parent node for each child node. Since every DODAG instance in RPL is connected to an OF, nodes can send data to their destination using the most effective route. Using an objective function that makes use of routing metrics, RPL creates routes and chooses the best parent for every child node [42].

3.3. Objective functions (OFs)

It splits the route picking and optimization from the basic protocol stuff like processing packets and forwarding them [43]. So, like, the main focus of the protocol is on dealing with these clashing requirements. Then there are extra modules that can be tweaked for specific goals - say, saving energy or boosting reliability [30], [32]. Apparently, there's this fancy term called “objective function” (OF) in RPL world. It is all about the rules and policies controlling how routes are picked and optimized to suit varied application demands [33]. An OF has two big jobs: figuring out how ranks are calculated based on routing metrics like energy, hop count, latency, throughput - you name it. And then deciding which parent node gets chosen based on that rank [30], [32]. Right now, RPL has two OFs that everyone agrees on: objective function zero (OF0) [30] and minimum rank with hysteresis objective function (MRHOF). But they just help make things work smoothly in the LLN world [33].

The RPL protocol in Contiki OS has two objective functions: MRHOF and OF0. Hop-count is the statistic used by OF0 to calculate node ranks, while expected transmission count (ETX) is a link quality measurement used by MRHOF. Furthermore, as reference [42] documents, earlier studies offered a number of metrics within RPL and other routing protocols: i) remaining energy of a node, ii) end to end delay, iii) received signal strength indicator (RSSI), and iv) local traffic in the network topology. In the upcoming section of the paper, we outline several instances of RPL objective functions along with their associated constraints to ensure network reliability.

3.3.1. OF0 based on hop count (HC)

In Contiki OS, the go-to objective function is OF0. It works by selecting neighbors with the lowest rank value based on hop count, ultimately enhancing network performance. It is kind of like choosing the shortest path to your destination. The root node kicks off with a rank of zero, then gradually climbs towards the leaf nodes. Without fancy load balancing tricks, OF0 favors nodes closest to the DODAG root as parents. By bumping up the rank with a positive scalar value, you get the node's rank. The 10-bit link color field, which serves as a recorded metric-you can decide what each bit means. Now, when it comes to selecting the preferred parent using (1) and (2), it is a bit of a math game. The equation factors in aspects like parent link metrics, hop-count, and ETX to make the right call [30]. OF0 stays mum on the specific metrics to use, but always goes for the parent with the lowest rank first. But OF0 does not assess the chosen parent's attributes or loads. This means nodes closer to the destination might get slammed with more traffic, potentially draining their batteries. And in a mobile setup, nodes with lower ranks could face link issues due to the environment, resulting in lost packets. To keep the network solid on the go, factors like received signal strength (RSS) or ETX are crucial at the link layer. As a result, using (1) and (2) as a recorded measure, the chosen preferred parent (Rp) is ascertained as (1), (2):

$$Rn = Rp + rank\_increase \tag{1}$$

$$rank\_increase = (Rf * Sp + Sr) * MinHopRankIncrease \tag{2}$$

Here, *step-of-rank (Sp)* represents a value related to parent link metrics and attributes such as hop-count or expected transmission count (ETX), and normalization factors are *stretch_of_rank (Sr)* and *rank factor (Rf)* [30]. Interestingly, OF0 is silent on which metric or metrics should be used to determine rank growth. A node operating with OF0 always choose the parent with the lowest rank as its first choice when it comes to parent selection. Additionally, OF0 takes into account the choice of a backup parent in the event that connectivity to the preferred parent is lost [30].

OF0 does not function as a mechanism for evaluating the attributes or burdens of the selected parent node. Consequently, nodes closer to the destination may experience higher traffic loads, potentially diminishing their battery life. Additionally, in mobile scenarios, nodes with lower rank values might encounter link quality challenges due to environmental factors, leading to packet loss. Ensuring network reliability in mobile environments necessitates utilizing metrics such as received signal strength (RSS) or ETX at the link layer.

3.3.2. Minimum rank hysteresis of (MRHOF) based on expected transmission count (ETX)

It basically takes this idea called "ETX" and combines it with how much juice (or energy) a node has left at the link layer. ETX, on the other hand, measures how likely it is for packet to reach its final destination during wireless communication. If you see big numbers when talking about ETX, that's bad news bears because it means lower throughput. Basically, when we talk about throughput here, we're looking at how smoothly data can flow from one node to another. The formula for figuring out ETX involves dividing 1 by $(df * dr)$.

$$Link\ ETX = 1 / (df * dr) \tag{3}$$

where "df represents the forward delivery ratio" and "dr represents the reverse delivery ratio."

Even though ETX calculation plays a big role in determining throughput based on how packets travel from sender to receiver nodes, it does not take into account other factors like interference from multiple hops along the way. ETX helps predict how many attempts are needed to get your precious data safely across without delays-reducing those annoying lags in network speeds. But relying solely on ETX is not foolproof for ensuring quick data transfers in networks where devices are constantly moving around. It is all about balance - weighing pros and cons of using metrics like ETX without painting an incomplete picture reinforces why having alternatives is always good practice when setting up networks that handle tons of data traffic daily.

3.3.3. OF-FL based on fuzzy logic model

In a study [31], researchers integrated numerous measurements into an objective function that used fuzzy logic to enhance routing decisions towards the DODAG root. Link quality, hop count, end-to-end delay, and node energy were all used to identify the best node to use as the preferred parent when sending data to the root. They evaluated the quality of nearby nodes by feeding the data from these measures into a fuzzy logic controller.

Several performance parameters were examined by the researchers throughout the evaluation process, including average hop count, average number of parent changes, average end-to-end delay, packet loss ratio, and average remaining node energy. The average hop count in dense networks stayed the same in all three network conditions, according to the findings. While OF-FL performed similarly to OF0 in high-density networks, it changed parents a little more frequently, which might have an effect on network stability. Through the reduction of end-to-end delay and the guarantee of high remaining energy among the majority of nodes, OF-FL shown improvements in network longevity. Compared to ETX, OF-FL showed a packet loss ratio that was comparable, but OF0 showed noticeably greater packet loss. As a result, OF-FL increased network lifetime, end-to-end latency, and RPL packet loss ratio. Nevertheless, the study is not appropriate for mobile wireless networks because it failed to include the key parameter required to identify and evaluate node mobility.

3.3.4. Routing maintenance (Trickle timer)

We want to sure we're not wasting energy or resources on unnecessary signaling. That's where the Trickle algorithm comes in-it is like the traffic cop of the network, making sure only the important get through [17], [34]. Trickle is all about being smart with when and how we send out signals. It is like a filter that adjusts itself based on what's happening in the network. If things are changing or there are inconsistencies, Trickle steps up the game and starts sending messages faster [17]. But once everything settles down, it takes a chill pill and slows things down to avoid spamming the network. Another cool thing about Trickle is its suppression mechanism. Basically, if a node sees that its neighbors are already spreading the word, it sits back and relaxes. So, when it comes to RPL, Trickle is like the guardian angel keeping the routing in check [17], [34].

4. RPL's OBJECTIVE FUNCTION ENHANCEMENTS

In this section, authors review the enhancements and extensions made to RPL's objective functions (OFs) since their inception, particularly concerning downward routing and routing maintenance. Authors delve into these extensions, providing detailed analysis while highlighting their significant drawbacks. Efforts have been made to address the gaps in RPL's objective functions in subsequent sections. Many of these endeavors have concentrated on devising OFs with composite routing metrics to reconcile conflicting routing demands within the same application domain. Another area of focus in a separate set of studies is the introduction of multipath routing to bolster the efficiency of OFs.

4.1. OF enhancements based on metric composition

Overcoming the problem of the RPL standards under specification with respect to metric composition has been the subject of numerous research studies. Consequently, lexical, additive, hybrid, and fuzzy-based compositions are among the strategies that have been suggested to combine the pertinent metrics. Parent selection in lexical composition is based on the first composition metric; in the event that two parents have similar values for this metric, the tie is broken using the second composition metric [35]. By integrating the weighted values of the relevant criteria, additive composition creates a composite value that ultimately determines which parent is favored [35]. In hybrid composition, two or more metrics are combined using lexical and additive techniques. Fuzzy logic is the foundation of fuzzy-based composition. We explore these extensions in the talk that follows. In the Table 1 RPL's OFs enhancements and their drawbacks are discussed in detail.

4.1.1. Hybrid composition enhancements

To maximize several performance characteristics, the authors of [35] suggest lexical and additive composition approaches to combine two routing metrics. They stress that to guarantee a routing protocol devoid of loops, it is crucial to preserve the monotonicity condition of the combined metric. For the composite metric to be valid in the situation of additive composition, the two-component metrics need to follow the same order relation. Nevertheless, lexical composition does not necessitate this restriction. According to the study, a combination of the HC and packet forwarding indication (PFI) metrics can be used to generate shorter pathways that avoid hostile or self-serving nodes. The results of the simulation show that lexical combination of both metrics provides similar latency as using simply the hop count metric but improves the detection of problematic nodes and the selection of trustworthy paths. Moreover, the authors demonstrate how better energy load distribution across nodes is achieved when residual energy (RE) and hop count measurements are combined, either lexically or additively, than when the hop count metric is used alone.

The scalable context-aware objective function (SCAOF) for those lossy and low power agricultural networks (A-LLNs)? This new function, introduced in source [36], looks at various metrics like remaining energy, ETX, availability info, hardware robustness, and affordable workload. But what's the deal with this integration? Well, the main goals are to keep nodes with low power levels in check and make sure we pick a solid path every time. Seems like they are really trying to optimize things here. Oh, and let's not forget about these new concepts called *ETX_Threshold* and *RE_Threshold*. They are supposed to help with application-consistent settings – whatever that means. They tested it against RPL-ETX using both real experiments and simulations. They looked at factors like packet loss rate, routing table size, *RoundTrip time (RTT)*, network churn. For apps that rely on A-LLNs, this protocol managed to cut down on network churn while boosting network lifespan.

Capone *et al.* [44], the discussion centers around MRPL protocols tailored to address mobility issues, primarily employing a proactive approach. In this method, the mobile node periodically calculates the RSSI value for all received signal messages, enabling it to self-detect mobility and manage disconnections accordingly. While this proposition offers valuable contributions and enhances performance, there remain areas for improvement, particularly regarding energy consumption. As the mobile node assumes responsibility for mobility support, its energy is depleted rapidly. Additionally, the periodic transmission of control messages results in high energy consumption and signaling overhead. Consequently, data loss occurs, compounded by a lingering disconnection issue, as the mobile node is unable to transmit packets during the handover process if it is detached.

As mentioned in the article, the conventional RPL protocol falls short in meeting the requirements of mobile nodes within wireless sensor networks (WSNs) [45], [46]. Consequently, numerous researchers have proposed diverse OFs and methodologies to address this limitation. Solapure and Kenchannavar [47], the authors introduce various OFs and combine them to enhance RPL's performance, catering to a range of smart IoT applications. They really dig into three key factors-content, ETX, and energy-to spruce up the protocol's blueprint. These metrics get some solo play and then mix it up together in a collaboration, spicing things up with a better trigger technique to whip up top-notch results. Picture this-marrying energy with content (EC) along with some aggregation and a juiced-up timer setup (*EC_En_Timer*) brings out snazzier PDR and shaves off the wait time for messages compared to the boring old OF method. Blending RE with ETX (EE) plus an upgraded timer set-up (*EE_En_Timer*) is shown as the money move for saving power. Hacking conversion time by half in the *En_Timer* mode. The EC and *EC_En_Timer* schemes flaunt high PDR rates and quick delivery times, making them ace picks for tasks like health monitoring where trustworthiness is king. On the flip side, RE, EE, and *EE_En_Timer* schemes serve energy conservation vibes which really shine in scenarios like keeping tabs on forests where power is gold. They are clear that you cannot just slap on any old operating formula across all IoT apps without a thought. Each application needs its special recipe tailored to its own flavor profile because let's face it - one size never fits all here.

Table 1. The RPL's OFs enhancements and their drawbacks

Ref.	Metrics	Type of metric composition	Brief description	Drawbacks
[48]	Neighbor variability (γ) and the last two RSSI	Additive	Mobility detection, control packet transmission adjustment	High packet loss, minimal signal overhead, but longer time to reconnect
[35]	HC and PFI orHC and RE	Lexical and additive	Integrating HC and PFI enhances the detection of malicious nodes within the network. Additionally, the combination of HC and RE facilitates load balancing across the network	Real testbed experiments were not conducted, and there is a risk of selecting low-quality paths despite the combination of metrics
[36]	RE, ETX, Link color and othercontext-aware metrics	Lexical and additive	It integrates RE, ETX, link color, and additional metrics to enhance reliability while avoiding nodes with depleted energy levels	Heightened risk of fragmentation, and the evaluation only covers up to 11 nodes. Additionally, there's still a possibility of selecting very low-quality paths
[37]	RE and ETX	additive	Combines RE and ETX forload-balancing	Only up to 6 nodes forevaluation. Very low-quality paths still canbe selected
[38]	Transmit power, energy and ETX	additive	It combines RE and ETX to improve reliability and energy efficiency, while also incorporating a mechanism to mitigate the impact of highly depleted nodes.	ack of reported or justified reliability regarding a claim and lack of clarification on how the intervals for DIO were selected.
[39]	HC, number of children and distance toparent	additive	Integrate the distance, number of children nodes, and the highest cost into a unified metric.	The risk of fragmentation is high, compounded by the absence of information regarding the simulation tool employed.
[40]	Signal integrity (SI) and ETX	additive	By introducing a novel stability metric and incorporating it with ETX, aim to construct a stable topology	Fewer control messages may indicate system stability, yet they could also imply unreliable links. The combination of SI and external factors (EXT) remains unclear.
[49]	RE and ETX	Lexical	It integrates RE and ETX to establish a topology that achieves both reliability and energy efficiency simultaneously.	Without real testbed experiments, there's a risk of selecting very low-quality paths.
[50]	HC and ETX	average	To mitigate the long single-hop issue, combine hop count and ETX by averaging ETX values.	Monotonicity is not maintained, and there's a challenge with excessive churn.
[31]	HC, energy, ETX and delay	Fuzzy-based	It integrates hop count, energy, link ETX, and delay to fulfill the most critical requirements.	Increased risk of fragmentation, and there's still a possibility of selecting very low-quality paths.
[51]	Delay, ETX and energy	Fuzzy- based	Integrating delay, ETX, and energy enhances stability, reliability, and energy efficiency.	enhanced stability and marginally improved delay lack justification. Additionally, the issue of selecting very low-quality paths persists.
[52] [53]	ARSSI, SPRR and SRNP	Fuzzy- based	Integrating ARSSI, SPRR, and SRNP enhances reliability by balancing the global quality of a path with the individual quality of its component links.	The assertion that the proposed metric prevents the selection of paths with low-quality links lacks com-prehensive support. Additionally, the incorporation of DIOs into the link estimation calculation remains unclear. This evaluation was conducted with a small number of nodes, totaling 10.
[54]	End-to-end delay, number of hops, ETX and link quality level (LQL)	Fuzzy	Objective function with new matric strategy and new method for DODAG creation	Minimal packet loss, minimal latency, and maximum energy with restricted mobility management
[44]	RSSI and more timers	Hybrid	Link monitoring using RSSI and more timers	Low overhead, low energy, high responsive
[55]	Average value of OFs and ARSSI	Additive	Extension to mRPL with new objective function	Low overhead, low energy, high responsive
[56]	cost matric mRank	Lexical and additive	Mobility detection and selection of parent using new cost matric mRank	High PDR and a short end-to-end latency, but failed to account for energy usage
[57]	FDTM-IoT	Fuzzy	FDTM-IoT has been used as OF in FDTM-RPL with dynamic, fuzzy and hierarchical trust model	Enhances packet performance, packet loss ratio, number of parent changes, and end-to-end latency considerably. Not much affected by attacks because SYBIL, RANK, and BLACKHOLE take place on the Internet of Things; thus, it is important to evaluate the effectiveness and resilience to alternative attacks.
[47]	Energy, content and ETX	Hybrid	Three metrics named as energy, content and ETX, individual and grouping with each other for different IoT applications	Compared to the default OF, energy + content - EC aggregation with an enhanced timer (EC_En_Timer) yields better results for PDR and latency delay. Better energy consumption results are obtained using the enhanced timer (EE_En_Timer) model and the Aggregation of residual energy (RE) + ETX (EE). Additionally, it is evident that the ETX and RE designs have extremely little overhead. An En_Timer design reduces conversion time by about fifty percent. The fact that it is limited to a single application is a drawback.
[58]	Hop count, RSSI and energy consumption of nodes	Hybrid	Hybrid objective function as combination of hop count, RSSI and energy consumption of nodes	When hybrid objective function with empirical stability awareness (HOFESA) is used in place of the original RPL and EC-OF protocols, PDR improves, power consumption decreases, convergence times shorten, and the quantity of DIO control messages is reduced. It guarantees network stability as well. It has not taken into account the matric ETX or any other matric for traffic control, node buffering, or delay to obtain better results.
[59]	Hop, signal-to-noise ratio (SNR) rate, link quality, and ETX energy consumption	Additive	Hop, SNR rate, link quality, and ETX energy consumption with distributed learning automata	Average lifetime, latency delay, energy consumption, and PDR in the network topology all perform well.

Typically used in LLNs, the RPL protocol selects preferable parents for packet routing towards the network topology's root node based on its OF. But it is possible that this traditional method does not completely satisfy all of the network's routing needs. Patwari *et al.* [58] suggest a hybrid objective function with empirical stability awareness (HOFESA), integrated at the network layer within CONTIKI, as a solution to this problem. Three parameters are combined by HOFESA: hop count, node energy usage, and RSSSI. Although this combination of metrics could lead to frequent modifications in favored parents, the algorithm includes both empirical and static thresholds to reduce this risk. The authors note improvements in PDR, shorter convergence times, lower power usage, and fewer DIO control messages through comparisons with standard RPL and EC_OF. However, the study did not take into consideration indicators like delay, node buffers, ETX, and traffic control.

4.1.2. Additive based composition enhancements

Uneven distribution and lopsided energy use among nodes are real issues in RPL networks. Using only ET as a metric might seem like a good idea at first. When they get hogged excessively because they deliver packets quicker. That could spell disaster for network partitioning and shorten its lifespan. On the flip side, solely focusing on energy might jeopardize reliability along the way. A mixed bag of metrics balancing energy and reliability called weighted energy-oriented composite metric. By considering both residual energy and ETX, this approach seems to hit the spot when it comes to conserving energy while keeping paths reliable. According to their findings, this newfound technique could prolong network life by up to 12%.

A novel composite metric for RPL Networks is introduced in [38]. This metric aims to balance energy consumption across nodes and extend the network's lifespan by taking into account both energy efficiency and dependability, as represented by the ETX metric. Known as the lifetime and latency aggregate metric (L2AM), this metric creates the principal metric by combining the link's transmission power and the residual energy of a node using an exponential function. The composite metric, which must be minimized when choosing the preferred parent, is then calculated by factoring the ETX metric into the primary metric. Comparative analysis with ETX RPL reveals that L2AM demonstrates superior performance, enhancing network lifetime by up to 56%.

Matsuura [39] really hit home the point about not just relying on hop count to figure out node rank. It could totally mess up the paths by miscalculating the actual distance. The more distance between nodes, the more energy the transmitter guzzles. So, if we keep going down this path, we'd end with routes gobbling up a ton of power. But wait, here comes the twist - the writers suggest this cool new metric that takes into account stuff like how close a node is to its maybe-parent, how many kiddos the maybe-parent has, and of course, the hop count. They put this fresh approach up against OF0 and the Karkazis [35] metric mash-up, looking at how long the devices last and how much juice they slurp up. The results speak for themselves - the new metric slashes power usage and boosts the DODAG's life span by a mile.

The authors discuss the reliability and instability problems related to RPL in [40]. They point out that frequent route modifications for RPL could have a detrimental effect on network performance. The authors note that while there are several metrics for RPL, there is not one that measures node stability. In order to close this gap, they present a brand-new stability index (SI) metric that assesses connection stability by taking into account the rate at which control messages are transmitted. The weighted quantity of DIO, DIS, and DAO control messages delivered within a given interval (the hearing window) is aggregated at each node, and then divided by the interval size to determine the SI. To provide each form of control message a distinct level of relevance, weighting is used [40]. The authors propose to further improve protocol dependability by integrating this new statistic with ETX. utilizing NS2 simulations, they assess the suggested and combined metrics and compare their results to those of RPL utilizing hop-count and ETX metrics for packet delivery rate, latency, and control message overhead. As compared to RPL utilizing hop count and ETX, simulation findings show that the new composite measure significantly reduces the CDF of control plane overhead by up to 90% and the average number of transmissions by up to 50%. Furthermore, in terms of packet delivery rate, SI-RPL and SI-ETX-RPL perform better than both ETX-RPL and HC-RPL, with the extent of the improvement varying with the size of the hearing window. On the other hand, SI-RPL and SI-ETX-RPL prioritize more stable and dependable pathways over more hops, exhibiting somewhat longer delay than HC-RPL [41].

The mobility-aware RPL (MARPL) approach is the main topic of [48], which explores mobility support in the RPL protocol. Two main processes are introduced by MARPL: mobility detection and control packet transmission adjustment. MARPL uses information from the network and data connection levels to identify mobility. It suggests that in order to choose new routes made by nodes-which are by nature static-and update parent nodes, neighbors need keep track of an adaptation score. In terms of overhead, packet delivery delay (PDD), preventing DODAG disconnections, and PDR, MARPL performs better, according to the results analysis. It also shows positive results in terms of the quantity of disconnections.

Adler *et al.* [59] introduce a novel mechanism termed DDSLA-RPL, which entails creating a list of optimal parent members based on factors such as hop count, link quality, SNR, and energy consumption (ETX). Child nodes are notified about accessible parent connections. The decision system approach, utilizing learning automata, dynamically determines and updates the weights of significant parameters. DDSLA-RPL incorporates parameters such as battery depletion index, node queuing, connection delay, and throughput as effective routing criteria. Unlike previous attempts using fuzzy logic or the K-Means algorithm, DDSLA-RPL employs distributed automata. This approach updates system parameters based on network feedback at specific intervals, thereby prolonging node lifetimes and enhancing network quality. Results demonstrate favorable performance in terms of node lifetime, energy fairness index, latency, graph consistency, and PDR within the network topology.

Anand and Tahiliani's work, described in [55], presents an improvement to their earlier RPL protocol [44], with the goal of addressing its shortcomings. Mobile nodes in mRPL ignore all other objective functions and choose parent nodes only based on the RSSI value. Nevertheless, this method could result in the choice of less-than-ideal paths. In order to address this problem, study [55] presents the “smarter-HOP” approach, which considers both the RSSI value and the average rankings of prospective parent nodes. Even with this enhancement, there is still a test of the protocol's performance against different mobility models and topologies, which limits how it may be assessed.

4.1.3. Lexical-based composition enhancements

Abreu *et al.* [49] presents a new energy-aware objective function (EAOF) named the Lexical Composite OF for the RPL protocol. The authors address the absence of energy-based metrics in current RPL objective functions. So, here is the deal, they are suggesting mixing the ETX metric with node residual energy to create a network setup that's both energy-efficient and reliable. What sets EAOF apart is how a node picks its preferred parent-it checks out neighbors with top-notch ETX ranks, and then decides based on which has the juiciest leftover energy. MAX-ETX and MIN_ENER come into play to manage subset size and prevent wild parent hopping, all for the sake of keeping things steady in the network. Now, when they put this concept to test using Cooja simulator [60], [61] with Contiki [62], magic happens. EAOF blows RPL MRHOF out of the water when it comes to network longevity and energy balance. Sure, there might be a teensy drop in PRR at times because EAOF values balance over pristine paths for that sweet extended network lifetime. This whole ETX-energy combo can really shake things up in the networking world.

The 6LoWPAN protocol and IPv6 routing protocol for low power and lossy networks (RPL). They are like the dynamic duo of IoT for wireless sensor networks, tackling connectivity challenges head-on. But let's be real, RPL has its fair share of struggles too, especially when it comes to keeping up with node movement and packet loss. A group of brilliant minds in reference [56] took matters into their own hands to give RPL a much-needed upgrade. They came up with this cool new cost measure that takes into account hops, RSSI value, and delay summation all at once. It is like a secret sauce that makes mobility management a piece of cake. These geniuses also cracked the code on how to spot those sneaky mobile nodes and pick their perfect match as parents. It is like giving each node its own personal global positioning system (GPS) to stay connected while sending data without breaking a sweat.

When a mobile node diverges from its original parent, the proposed protocol imRPLv2 recognizes this as node mobility and initiates parent selection by sending a notification message to identify a new parent. Results from simulations show that imRPLv2 delivers low end-to-end latency while achieving a high PDR. Additionally, the mobile detection technique enables mobile nodes to choose their replacement parent node in advance of disconnecting, guaranteeing uninterrupted data forwarding and minimizing packet loss.

4.1.4. Cross-layer based composition enhancements

Abdessalem *et al.* [63] introduces RPL-SCSP, a cross-layer composition that merges the ETX and queue load metrics to enhance quality of service (QoS) support within the network. RPL-SCSP proposes a parent selection process primarily based on the queue load, denoted as *nqpacket*. Specifically, a parent with a queue load falling between one and a predefined threshold, S, is prioritized as the preferred parent. In cases where multiple parents meet this criterion, selection is determined based on their ETX values. Similarly, if all parents have a queue load less than one or greater than S, preference is given based on ETX values. Simulation experiments demonstrate that RPL-SCSP effectively reduces end-to-end delay and prolongs network lifetime.

4.1.5. Average-based composition enhancements

Let's dig into the fascinating study outlined in study [50]. Imagine a scenario where RPL in extensive networks relies solely on hop count or transmission cost predictions. Well, the brilliant minds behind this research found a way to tackle this issue head-on. They introduced the concept of PER-HOP ETX, a game-changer in the world of routing protocols. Instead of just focusing on the number of hops, PER-

HOP ETX takes into account both hop count and ETX parameters when determining the best path. It is like finding the perfect balance between efficiency and reliability. By incorporating PER-HOP ETX into the mix, the research team noticed significant improvements in network performance. The idea is simple yet powerful by calculating the rank using a combination of ETX values and hop count, better routing decisions can be made. It is like having a GPS system that not only looks at the shortest route but also considers the road conditions for a smoother journey. To put this theory to the test, the researchers compared PER-HOP ETX with other existing methods using Cooja. The results were impressive-lower latency, reduced power consumption, and improved packet delivery ratio in dense networks. It is like upgrading your car to a hybrid model and instantly seeing the benefits in terms of efficiency and performance. In a nutshell, PER-HOP ETX is a game-changer in the world of routing protocols. It is like having a supercharged engine that not only gets you to your destination faster but also ensures a smooth ride along the way. The research opens up new possibilities for creating more robust and reliable networks, making our digital connections stronger than ever before. So, next time you're navigating the intricate web of network paths, remember the power of PER-HOP ETX.

4.1.6. Fuzzy-based composition enhancements

The whole deal with using fuzzy-logic OFs for RPL has been explored extensively in a bunch of papers. Like, check out the folks in [31], they are all about pointing out the downsides of relying solely on one metric for objectives. They argue that with different performance goals all over the place, even blending a couple of measures might not cut it for meeting the diverse needs of many applications. And just optimizing for two routing variables could help some network performance stuff but mess up other things at the same time. Throwing in some ETX and latency data might make it easier for the network to find dependable routes with low latency, but it could drain some routers' batteries quicker than you'd think. So, they are all in for cooking up a super comprehensive objective function that combines a bunch of routing metrics to make all the important factors happy in one go. They are all about this fuzzy-logic OF (FL-OF) – it is this fuzzy logic magic that lumps together four key routing metrics: hop count, node energy, connection quality, and end-to-end delay. Their findings show that FL-OF tends to cut down the average hop count in crowded networks compared to MRHOF. FL-OF scores way better on packet delivery than OF0 and almost catches up to MRHOF with ETX. Plus, FL-OF does a solid job at spreading the load out among nodes, making sure energy use is nice and balanced [64].

You ever hear about this other way of mixing up routing metrics in a study? Yep, some researchers detailed it in their work [51]. So, what they did was blend three different factors - delay, ETX, and energy - using a kind of fuzzy process. First off, they tackled delay and ETX to figure out the QoS, whatever that means. Then came the second round where energy gets thrown into the mix with this calculated QoS thing. They put this method to test in a real network with twenty-eight sensor nodes, pitting it against ETX-RPL. They went head-to-head looking at things like how much power is used up, how many packets go missing, and how often nodes switch between preferred parents. The fuzzy-based method performs up to 20% better in packet loss ratio than ETX-RPL, according to the results, and it somewhat reduces end-to-end latency. Furthermore, the suggested method is found to create a topology with more stable routes, recording an hourly average of 6.63 parent changes, as opposed to ETX-RPL's 43.52 average.

In this fascinating study from [54], they dive into a whole new world of technology with their fancy objective function OF-FL (objective function based on fuzzy logic) and the innovative Co-RPL protocol. The mission here is to fix all the issues that past OFs could not handle. Co-RPL is like a souped-up version of RPL, complete with a corona mechanism for that extra touch to amp up mobility and tackle those pesky topology changes head-on. They are both showing significant improvement thanks to the tag team of OF-FL and Co-RPL.

Hashemi and Aliee [57] provide FDTM-RPL, an improved RPL protocol that builds upon the current protocol. As an OF, this update includes the fuzzy, dynamic, and hierarchical trust model for the internet of things (FDTM-IoT). Three criteria are used by FDTM-IoT to assess trustworthiness: quality of peer-to-peer communication (QPC), contextual information (CI), and QoS. The FDTM-RPL operates on the basis of this trust paradigm. Through the use of the Cooja simulator, the authors ran simulations that showed gains in network performance. When compared to traditional protocols, notable improvements were seen in the average number of parent modifications, end-to-end delay, and packet loss ratio. Moreover, FDTM-RPL demonstrates resistance to well-known IoT threats such as RANK, SYBIL, and BLACKHOLE. Nonetheless, further evaluation is needed to assess its effectiveness and resilience against other types of attacks.

Have you heard about the new Opt-FLQERM routing statistic? It is all the buzz in [52], [53]. The folks behind this nifty tool have combined three key metrics to create a comprehensive score: ARSSI, SPRR, and SRNP. By using fuzzy logic, they churn out a value ranging from 0 to 100. But what does it all mean?

well the lower the score, the better the path. Picture this - imagine each link having its own quality ranking. The smart cookies who came up with Opt-FLQERM believed that by flipping these rankings upside down, they could pinpoint top-notch routes with fewer hops and steer clear of shady links. Now comes the fun part - testing it out! They pitted Opt-FLQERM against RPL, ETX-RPL, and four-bit CTP metrics in the Cooja simulator rodeo [65]. Opt-FLQERM boasted minimal packet loss, snappy end-to-end delays, and a low rate of parent swaps (churn). This success dance was particularly evident when comparing it to ETX-RPL's cautious approach of only considering post-topology data traffic to gauge link quality. By blending both control signals and data traffic into its link quality recipe early on, it paints a more accurate picture of network pathways during setup [52].

The research described in study [35] marks the initial effort to quantify routing metrics within RPL, facilitating their lexical or additive fusion. Although the study introduces a promising method to balance energy distribution among nodes by integrating node energy (RE) with hop-count, it overlooks discussing how this amalgamation influences network reliability, a pivotal performance metric. Additionally, it remains ambiguous whether the study utilizes the aggregated value of the RE metric or a local optimum value. Meanwhile, the study cited as [37] faces a notable limitation in its simulation experiments, involving only up to six nodes. Such a small-scale setup might not suffice to draw robust conclusions. Furthermore, the authors omit an exploration of how the composite metric could impact network reliability.

The deficiencies identified in the articles referenced as [35] and [37] are tackled in [49]. Initially, the author introduces the MIN_ENER parameter to mitigate network churn caused by energy-related parent switches. Additionally, the study incorporates a reliability-focused performance assessment of the composite metric. Nonetheless, the simulation experiments utilize only 25 nodes, limiting the generalizability of the conclusions to larger networks.

While the study referenced as [38] asserts an increase in network lifetime without compromising network reliability, it fails to provide any supporting results regarding reliability or rationale for reaching this conclusion. Additionally, the authors employ their custom simulator for evaluation, potentially lacking features compared to established simulators like Cooja. Notably, the study sets the Trickle timer interval for emitting DIOs to 1 hour, suggesting that only one interval is configured in their simulations, deviating from the typical operation of the Trickle protocol, which can be confusing.

In study [36], the utilization of SCAOF by nodes poses a heightened risk of layer 2 fragmentation. This arises from the necessity for DIOs to be transmitted by these nodes to accommodate a comparatively extensive pool of parameters in their headers. Such a scenario presents a significant challenge in low-power and lossy networks (LLNs), as it elevates the likelihood of errors and packet loss, particularly in multipath routing configurations.

The monotonicity property of the combined metric is not satisfied, which puts the network at danger of loop formation. This is a significant problem with the PER-HOP ETX metric that was suggested in [50]. The issue with the work in [39] is that real testbed deployments provide challenges for the calculation of node positions. As a result, live physical distance estimations are likely to be inaccurate (like RSSI) or energy-intensive (like GPS) [66], [67].

The PER-HOP ETX metric, you know the one from [50], has a bit of a problem. It kind a forgets to follow the monotonicity rule, which could cause loops in the network. And that study cited as [39]. It is difficult figuring out where the nodes are in actual runs. Resulting in distance guesses that not too accurate like RSSI or super power-hungry like GPS [66], [67].

In study [40], the stability of nodes and the routing topology is assessed using the frequency of control messages (DIOs, DAOs, and DISs). However, it is important to note that a higher frequency of control messages does not necessarily indicate higher instability in all cases. For example, a node with more children will naturally need to transmit a greater number of DAOs compared to a node with fewer children. In such cases, the increased control overhead is caused by the number of children rather than instability issues. A more refined approach would involve basing the measurement of the instability index solely on DIO messages, providing a more elegant solution.

It is acknowledged that fuzzy-based techniques are more sophisticated than other ways, particularly when there are several instances operating within the same RPL topology [68]. For example, as stated in [31], sending more than four parameters in the DIO metric container may increase the likelihood of fragmentation, which in turn increases overhead because bigger DIO sizes are required [68]. The stability of routes is cited in [51] as the reason for the purported superiority of the suggested strategy; however, no justification is offered for the fuzzy-based approach's inherent stability. This absence of reasoning also applies to the minor improvement in latency. It is unclear from the technique in [52] how control traffic messages (DIOs) are included in the link estimation computation. Last but not least, Opt-FLQERM favors paths with fewer hops, which may result in the selection of routes with subpar single-hop links.

5. MOBILITY IMPACT WITH RPL

Because RPL was first intended for static networks, it is not suitable for managing node mobility within a topology. Still, progress can be made to successfully handle these obstacles. For example, if a node breaks away from the current DODAG, it will lose data packets until it finds a new preferred parent, either in the same DODAG or one close by. Network performance is indirectly impacted by this disturbance. This article's main goal is to investigate several suggested protocols or techniques that promote micro-mobility, making it possible to forecast node movements or disconnections and to quickly repair broken links so that new pathways can be established. These protocols prevent data loss and guarantee the nodes in the network are continuously and effectively accessible.

The network topology changes when a node fails or moves, which causes the node to lose contact with its parents and children. As a result, data transmission capacity in compliance with RPL standard parameters is lost. The node must refresh its knowledge of nearby nodes and routing paths, which includes details like the list of parent nodes, preferred parent, and node rank, to overcome this difficulty. RPL addresses this problem by using a self-healing approach in which nodes keep constant communication to adjust to changes in the network topology and dynamically updated routing decisions are made. Let's first look at the main changes brought about by the node's mobility at the mobile node (MN) and its neighbors, which causes a topological change, as shown in Figure 5.

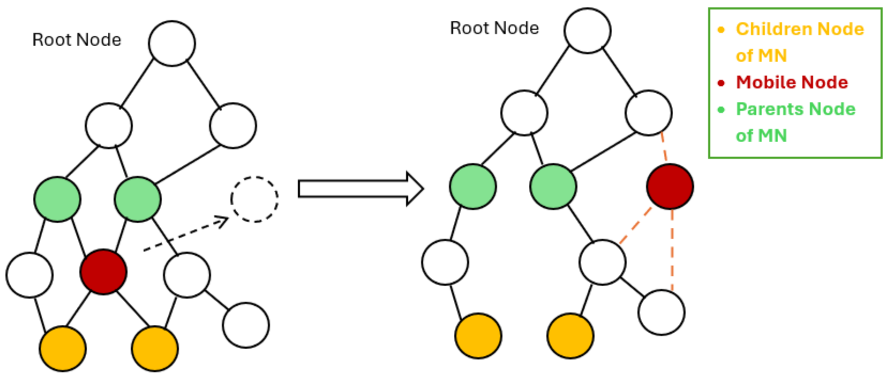

Figure 5. Change in the route instigated by the mobility of the node [69]

5.1. The mobile node

Once a mobile node (MN) strays beyond a specific range, it bids farewell to the network. As it cannot chat with its pals in the DODAG. Feeling lonely and disconnected, the MN tries to hitch a ride with some neighboring nodes for a fresh start. There are two ways to get back into the game. When another router sends our MN a DIO message, it is showtime for method number one. Our resourceful MN takes that message and works some magic on its settings - tweaking parent list, preferred parent, rank, routing table-all to carve an upward route. It does not stop there; it spreads word of these changes through an updated DIO message and pings its kids with a DAO message for the way down. When no DIO message is in sight-That's when strategy two swings into action! MN starts integrating into the DODAG tree by putting out solicitation messages, or DIS.

5.2. The neighbor nodes

To maintain connectivity between mobile nodes and their neighboring counterparts, each node must attempt to receive DAO messages and broadcast DIO messages to its children on a regular basis, as determined by the Trickle timer. As a result, a node loses data as it moves, separating itself from its neighbors, which interferes with routing routes within the mobile network. To solve this problem, a node assumes it is beyond of its range if it does not get any DAO or DIO messages from the MN. As a result, the routing table removes the matching entry for that Minnesota and removes it from the list of neighbors and parents. It then goes into a waiting state where it awaits control messages from the other nodes so that it can update its state and verify connectivity for both paths, up and down [69].

5.3. Problems and limitations of mobility in to RPL

The RPL stuff is not cutting it when it comes to dealing with nodes that like to move around and the ever-changing network scene. Mobile nodes (MN) face lots of bumps and glitches with RPL, making it tough for them to stay connected, especially in fast-paced situations. It is all good for networks that don not move, but when things start shaking up, RPL struggles to keep up with the pace [70].

Let talk about how this whole mobility detection thing depends on whether those DIO messages show up or not. These messages can be a bit slow to arrive, which messes with RPL's groove and makes it hard to fix things quickly. Mobile nodes (MN) lose out, and data takes a hit. Real-time applications suffer the most, and that's a big deal in the networking world. But that just means more signals flying around, more crashes, more power burned, and more data lost. So, we need to find a better way to handle mobility without drowning in all these messages. Then there's the sticky situation of responding to nodes on the move. If a node disconnects, RPL only knows when it hears from a new buddy, causing delays and making the MN sweat it out a bit too long. This waiting game leads to lost packets and frustrations all around.

We need a slick new plan that thinks ahead and deals with these changes. RPL does not quite have what it takes to keep things running smoothly when nodes start roaming. It struggles to find a solid path with all these mobile nodes (MN) bouncing around.

Research shows that RPL has a tough time managing mobility, especially when it comes to sending out those important control messages. Without these messages, it is hard to spot when things go haywire in the network. We need a smarter way to track movement in the network and pick the best connections to keep things flowing smoothly. These challenges show us that RPL needs a serious upgrade to handle the ups and downs of mobility in style.

6. CONCLUSION

As the article explains, on the IoT, devices that are inherently mobile nodes are referred to as mobile devices, or mobility. Because it results in intermittent connections and disconnection between nodes, which has a significant impact on network efficiency and performance, mobility is still an interesting topic. Furthermore, node energy conservation might be difficult in networks with constrained resources. The current routing protocol, RPL, is ineffective at responding to node movement within the network, despite being designed by the IETF for static systems. To do this, numerous researchers have improved the RPL protocol for low power and lossy networks, overcoming the drawbacks of the conventional RPL. Improved protocols allow for improved mobile node connectivity while conserving energy. incorporating a better mobility detection technique that continuously measures the separation between each mobile node and its parent node. The study demonstrates that many of the issues that the RPL routing protocol still has with mobility and OFs include the lack of an effective methodology to reduce control messages, the recreation of DODAG, the methodology for monitoring mobility and choosing a preferred parent, the node's energy consumption, and data loss, all of which further make mobility into account with different fundamentals.

ACKNOWLEDGMENTS

The authors want to thank the Department of Computer Engineering, CHARUSAT university, for providing the facilities and support for completing this research work.

FUNDING INFORMATION

No funds are provided for this research work from any funding agencies.

AUTHOR CONTRIBUTIONS STATEMENT

Ditixa Vyas, a PhD scholar, contributed to this research under the supervision of Dr. Ritesh Patel. Ditixa devised the main conceptual ideas, worked out almost all of the technical details, and performed the simulation for the suggested experiments by Dr. Ritesh and written the whole manuscript.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ditixa Vyas	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
Dr. Ritesh Patel						✓				✓		✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest to report regarding the present study.

INFORMED CONSENT

The protection of privacy is a legal right that must not be breached without individual informed consent. In cases where the identification of personal information is necessary for scientific reasons, authors should obtain full documentation of informed consent, including written permission from the patient prior to inclusion in the study. Incorporate the following (or a similar) statement: We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

When papers talk about using people or animals, authors should make it clear that the research followed all national rules and institutional policies, and it was approved by the authors' institutional review board or a similar committee. The Helsinki Declaration's tenets must guide all investigations involving human subjects. Authors must also identify the committee or review board approving the experiments and provide a statement indicating approval of the research. Incorporate the following (or a similar) statement: The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee; or: The research related to animal use has been complied with all the relevant national regulations and institutional policies for the care and use of animals.

DATA AVAILABILITY

No new data was created during this study. Only simulations have been taken place and based on that the analysis has been done. So, data sharing is not applicable to this article.

REFERENCES

[1] C. Bormann, M. Ersue, and A. Keranen, *Terminology for constrained-node networks*, RFC 7228.

[2] J. A. Gutierrez, M. Naeve, E. Callaway, M. Bourgeois, V. Mitter, and B. Heile, "IEEE 802.15.4: a developing standard for low-power low-cost wireless personal area networks," *IEEE Network*, vol. 15, no. 5, pp. 12–19, 2001, doi: 10.1109/65.953229.

[3] IEEE 802 Working Group, "IEEE standard for local and metropolitan area networks--part 15.4: low-rate wireless personal area networks (LR-WPANs)." IEEE, Piscataway, NJ, USA, Jun. 16, 2011, doi: 10.1109/IEEESTD.2011.6012487.

[4] J. P. Vasseur and A. Dunkels, "Interconnecting smart objects with IP: the next internet," *Interconnecting Smart Objects with IP: The Next Internet*, pp. 1–407, 2010, doi: 10.1016/C2009-0-20667-2.

[5] S. Deering and R. Hinden, *Internet protocol, version 6 (IPv6) specification*, RFC 2460, 1998.

[6] H. Lamaazi, N. Benamar, and A. J. Jara, "RPL-based networks in static and mobile environment: a performance assessment analysis," *Journal of King Saud University - Computer and Information Sciences*, vol. 30, no. 3, pp. 320–333, Jul. 2018, doi: 10.1016/j.jksuci.2017.04.001.

[7] G. Rao. S, Z. Suryady, U. Sarwar, and M. Abbas, "A gateway solution for IPv6 wireless sensor networks," in *2009 International Conference on Ultra Modern Telecommunications and Workshops*, Oct. 2009, pp. 1–6, doi: 10.1109/ICUMT.2009.5345603.

[8] T. Teubler, M. A. Hail, and H. Hellbruck, "Transparent integration of non-IP WSN into IP based betworks," in *2012 IEEE 8th International Conference on Distributed Computing in Sensor Systems*, May 2012, pp. 353–358, doi: 10.1109/DCOSS.2012.10.

[9] A. G. F. Elias, J. J. P. C. Rodrigues, L. M. L. Oliveira, and L. Zhou, "IPv4/IPv6 transition mechanisms for ubiquitous wireless sensor networks monitoring," in *2013 Fifth International Conference on Ubiquitous and Future Networks (ICUFN)*, Jul. 2013, pp. 192–196, doi: 10.1109/ICUFN.2013.6614810.

[10] T. Clausen, U. Herberg, and M. Philipp, "A critical evaluation of the IPv6 routing protocol for low power and lossy networks (RPL)," in *2011 IEEE 7th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, Oct. 2011, pp. 365–372, doi: 10.1109/WiMOB.2011.6085374.

[11] G. Montenegro, N. Kushalnagar, J. Hui, and D. Culler, *Transmission of IPv6 packets over IEEE 802.15.4 networks*, RFC 4944. 2007.

[12] N. Accettura and G. Piro, "Optimal and secure protocols in the IETF 6TiSCH communication stack," in *2014 IEEE 23rd International Symposium on Industrial Electronics (ISIE)*, Jun. 2014, pp. 1469–1474, doi: 10.1109/ISIE.2014.6864831.

[13] Y. Al-Nidawi and A. H. Kemp, "Mobility aware framework for timeslotted channel hopping IEEE 802.15.4e sensor networks," *IEEE Sensors Journal*, vol. 15, no. 12, pp. 7112–7125, Dec. 2015, doi: 10.1109/JSEN.2015.2472276.

[14] M. R. Palattella, N. Accettura, L. A. Grieco, G. Boggia, M. Dohler, and T. Engel, "On optimal scheduling in duty-cycled industrial IoT applications using IEEE802.15.4e TSCH," *IEEE Sensors Journal*, vol. 13, no. 10, pp. 3655–3666, Oct. 2013, doi: 10.1109/JSEN.2013.2266417.

[15] D. Dujovne, T. Watteyne, X. Vilajosana, and P. Thubert, "6TiSCH: deterministic IP-enabled industrial internet (of things)," *IEEE Communications Magazine*, vol. 52, no. 12, pp. 36–41, Dec. 2014, doi: 10.1109/MCOM.2014.6979984.

[16] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, Mar. 2002, doi: 10.1016/S1389-1286(01)00302-4.

[17] P. Levis, N. Patel, D. Culler, and S. Shenker, "Trickle: a self-regulating algorithm for code propagation and maintenance in wireless sensor networks," *1st Symposium on Networked Systems Design and Implementation, NSDI 2004*, 2004.

[18] T. Winter *et al.*, *RPL: IPv6 routing orotocol for low power and lossy networks*, RFC 6550. 2012.
[19] A. Brandt, J. Buron, and G. Porcu, *Home automation routing requirements in low-power and lossy networks*. RFC 5826, 2010.
[20] J. Martocci, P. De Mil, N. Riou, and W. Vermeylen, *Building automation routing requirements in low-power and lossy networks*, RFC 5867. 2010.
[21] Q. Tang, L. Yang, G. B. Giannakis, and T. Qin, "Battery power efficiency of PPM and FSK in wireless sensor networks," in *MILCOM 2005 - 2005 IEEE Military Communications Conference*, 2007, pp. 1–7, doi: 10.1109/MILCOM.2005.1606004.
[22] A. Meier, T. Rein, J. Beutel, and L. Thiele, "Coping with unreliable channels: Efficient link estimation for low-power wireless sensor networks," in *2008 5th International Conference on Networked Sensing Systems*, Jun. 2008, pp. 19–26, doi: 10.1109/INSS.2008.4610885.
[23] J. Zhao and R. Govindan, "Understanding packet delivery performance in dense wireless sensor," *SenSys'03: Proceedings of the First International Conference on Embedded Networked Sensor Systems*, pp. 1–13, 2003.
[24] K. Pister, P. Thubert, S. Dwars, and T. Phinney, *Industrial routing requirements in low-power and lossy networks*, RFC 5673. 2009.
[25] M. Dohler, T. Watteyne, T. Winter, and D. Barthel, *Routing requirements for urban low-power and lossy networks*, RFC 5548. 2009.
[26] A. Brandt, E. Baccelli, R. Cragie, and P. van der Stok, *Applicability statement: the use of the routing protocol for low-power and lossy networks (RPL) protocol suite in home automation and building control*, RFC 7733. 2016.
[27] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, and A. Jamalipour, "Wireless body area networks: a survey," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 3, pp. 1658–1686, 2014, doi: 10.1109/SURV.2013.121313.00064.
[28] H.-S. Kim, J. Ko, D. E. Culler, and J. Paek, "Challenging the IPv6 routing protocol for low-power and lossy networks (RPL): a survey," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 4, pp. 2502–2525, 2017, doi: 10.1109/COMST.2017.2751617.
[29] H. Tian, Z. Qian, X. Wang, and X. Liang, "QoI-aware DODAG construction in RPL-based event detection wireless sensor networks," *Journal of Sensors*, vol. 2017, pp. 1–9, 2017, doi: 10.1155/2017/1603713.
[30] P. Thubert, *Objective function zero for the routing protocol for low power and lossy networks (RPL)*, RFC 6552. 2012.
[31] O. Gaddour, A. Koubaa, N. Baccour, and M. Abid, "OF-FL: QoS-aware fuzzy logic objective function for the RPL routing protocol," in *2014 12th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, May 2014, pp. 365–372, doi: 10.1109/WIOPT.2014.6850321.
[32] O. Gnawali and P. Levis, *The minimum rank with hysteresis objective function*, IETF RFC 6. 2012.
[33] J. Vasseur, M. Kim, K. Pister, N. D. N., and D. Barthel, *Routing metrics used for path calculation in low-power and lossy networks*, RFC 6551. 2012.
[34] P. Levis, T. Clausen, J. Hui, O. Gnawali, and J. Ko, *The trickle algorithm*. 2011.
[35] P. Karkazis *et al.*, "Design of primary and composite routing metrics for RPL-compliant wireless sensor networks," in *2012 International Conference on Telecommunications and Multimedia (TEMU)*, Jul. 2012, pp. 13–18, doi: 10.1109/TEMU.2012.6294705.
[36] Y. Chen, J.-P. Chanet, K.-M. Hou, H. Shi, and G. De Sousa, "A scalable context-aware objective function (SCAOF) of routing protocol for agricultural low-power and lossy networks (RPAL)," *Sensors*, vol. 15, no. 8, pp. 19507–19540, Aug. 2015, doi: 10.3390/s150819507.
[37] L.-H. Chang, T.-H. Lee, S.-J. Chen, and C.-Y. Liao, "Energy-efficient oriented routing algorithm in wireless sensor networks," in *2013 IEEE International Conference on Systems, Man, and Cybernetics*, Oct. 2013, pp. 3813–3818, doi: 10.1109/SMC.2013.651.
[38] S. Capone, R. Brama, N. Accettura, D. Striccoli, and G. Boggia, "An energy efficient and reliable composite metric for RPL organized networks," in *2014 12th IEEE International Conference on Embedded and Ubiquitous Computing*, Aug. 2014, pp. 178–184, doi: 10.1109/EUC.2014.33.
[39] H. Matsuura, "New routing framework for RPL: constructing power-efficient wireless sensor network," in *2014 IEEE Network Operations and Management Symposium (NOMS)*, May 2014, pp. 1–9, doi: 10.1109/NOMS.2014.6838235.
[40] X. Yang, J. Guo, P. Orlik, K. Parsons, and K. Ishibashi, "Stability metric based routing protocol for low-power and lossy networks," in *2014 IEEE International Conference on Communications (ICC)*, Jun. 2014, pp. 3688–3693, doi: 10.1109/ICC.2014.6883895.
[41] N. Cam-Winget, J. Hui, and D. Popa, *Applicability statement for the routing protocol for low-power and lossy networks (RPL) in advanced metering infrastructure (AMI) networks*, RFC 8036. 2017.
[42] I. H. Urama, H. Fotouhi, and M. M. Abdellatif, "Optimizing RPL objective function for mobile low-power wireless networks," in *2017 IEEE 41st Annual Computer Software and Applications Conference (COMPSAC)*, Jul. 2017, pp. 678–683, doi: 10.1109/COMPSAC.2017.185.
[43] M. Bouaziz, A. Rachedi, and A. Belghith, "EC-MRPL: an energy-efficient and mobility support routing protocol for internet of mobile things," in *2017 14th IEEE Annual Consumer Communications & Networking Conference (CCNC)*, Jan. 2017, pp. 19–24, doi: 10.1109/CCNC.2017.7983074.
[44] H. Fotouhi, D. Moreira, and M. Alves, "mRPL: boosting mobility in the internet of things," *Ad Hoc Networks*, vol. 26, pp. 17–35, Mar. 2015, doi: 10.1016/j.adhoc.2014.10.009.
[45] L. Mainetti, L. Patrono, and A. Vilei, "Evolution of wireless sensor networks towards the Internet of things: a survey," in *2011 International Conference on Software, Telecommunications and Computer Networks, SoftCOM 2011*, 2011, pp. 1–6.
[46] N. Khalil, M. R. Abid, D. Benhaddou, and M. Gerndt, "Wireless sensors networks for internet of things," in *2014 IEEE Ninth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP)*, Apr. 2014, pp. 1–6, doi: 10.1109/ISSNIP.2014.6827681.
[47] S. S. Solapure and H. H. Kenchannavar, "Design and analysis of RPL objective functions using variant routing metrics for IoT applications," *Wireless Networks*, vol. 26, no. 6, pp. 4637–4656, Aug. 2020, doi: 10.1007/s11276-020-02348-6.
[48] J. Kniess and V. de Figueiredo Marques, "MARPL: a crosslayer approach for Internet of things based on neighbor variability for mobility support in RPL," *Transactions on Emerging Telecommunications Technologies*, vol. 31, no. 12, Dec. 2020, doi: 10.1002/ett.3931.
[49] C. Abreu, M. Ricardo, and P. M. Mendes, "Energy-aware routing for biomedical wireless sensor networks," *Journal of Network and Computer Applications*, vol. 40, pp. 270–278, Apr. 2014, doi: 10.1016/j.jnca.2013.09.015.
[50] W. Xiao, J. Liu, N. Jiang, and H. Shi, "An optimization of the object function for routing protocol of low-power and Lossy networks," in *The 2014 2nd International Conference on Systems and Informatics (ICSAI 2014)*, Nov. 2014, pp. 515–519, doi: 10.1109/ICSAI.2014.7009341.
[51] P.-O. Kamgueu, E. Nataf, and T. Ndie Djotio, "On design and deployment of fuzzy-based metric for routing in low-power and lossy networks," in *2015 IEEE 40th Local Computer Networks Conference Workshops (LCN Workshops)*, Oct. 2015, pp. 789–795, doi: 10.1109/LCNW.2015.7365929.
[52] S. Rekik, N. Baccour, M. Jmaiel, and K. Drira, "Low-power link quality estimation in smart grid environments," in *2015 International Wireless Communications and Mobile Computing Conference (IWCMC)*, Aug. 2015, pp. 1211–1216, doi: 10.1109/IWCMC.2015.7289255.
[53] S. Rekik, N. Baccour, M. Jmaiel, and K. Drira, "Holistic link quality estimation-based routing metric for RPL networks in smart

grids," in *2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Sep. 2016, pp. 1–6, doi: 10.1109/PIMRC.2016.7794925.

[54] O. Gaddour, A. Koubâa, and M. Abid, "Quality-of-service aware routing for static and mobile IPv6-based low-power and lossy sensor networks using RPL," *Ad Hoc Networks*, vol. 33, pp. 233–256, 2015, doi: 10.1016/j.adhoc.2015.05.009.

[55] M. C. R. Anand and M. P. Tahiliani, "mRPL++: Smarter-HOP for optimizing mobility in RPL," in *2016 IEEE Region 10 Symposium (TENSYMP)*, May 2016, pp. 36–41, doi: 10.1109/TENCONSpring.2016.7519374.

[56] P. Satanasaowapak and C. Khunboa, "The improvement of node mobility in RPL to increase transmission efficiency," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 5, pp. 4238–4249, Oct. 2019, doi: 10.11591/ijece.v9i5.pp4238-4249.

[57] S. Y. Hashemi and F. S. Aliee, "Fuzzy, dynamic and trust based routing protocol for IoT," *Journal of Network and Systems Management*, vol. 28, no. 4, pp. 1248–1278, Oct. 2020, doi: 10.1007/s10922-020-09535-y.

[58] A. E. Hassani, A. Sahel, A. Badri, and E. M. Ilham, "A hybrid objective function with empirical stability aware to improve RPL for IoT applications," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 3, pp. 2350–2359, Jun. 2021, doi: 10.11591/ijece.v11i3.pp2350-2359.

[59] M. H. Homaei, S. S. Band, A. Pescape, and A. Mosavi, "DDSLA-RPL: dynamic decision system based on learning automata in the RPL protocol for achieving QoS," *IEEE Access*, vol. 9, pp. 63131–63148, 2021, doi: 10.1109/ACCESS.2021.3075378.

[60] A. R. Jadhao and S. S. Solapure, "Analysis of routing protocol for low power and lossy networks (RPL) using Cooja simulator," in *2017 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)*, Mar. 2017, pp. 2364–2368, doi: 10.1109/WiSPNET.2017.8300183.

[61] F. Osterlind, A. Dunkels, J. Eriksson, N. Finne, and T. Voigt, "Cross-level sensor network simulation with COOJA," in *Proceedings. 2006 31st IEEE Conference on Local Computer Networks*, Nov. 2006, pp. 641–648, doi: 10.1109/LCN.2006.322172.

[62] GitHub, "Contiki-os," GitHub, 2006, [Online]. Available: https://github.com/contiki-os/contiki/tree/master/core/net/rpl.c (accessed on 27 September 2023)

[63] R. Ben Abdessalem and N. Tabbane, "RPL-SCSP: a network-MAC cross-layer design for wireless sensor networks," in *Proceedings of Ninth International Conference on Wireless Communication and Sensor Networks*, 2014, pp. 27–35.

[64] B. Ghaleb *et al.*, "A survey of limitations and enhancements of the IPv6 routing protocol for low-power and lossy networks: a focus on core operations," *IEEE Communications Surveys and Tutorials*, vol. 21, no. 2, pp. 1607–1635, 2019, doi: 10.1109/COMST.2018.2874356.

[65] R. Fonseca, O. Gnawali, K. Jamieson, and P. Levis, "Four-bit wireless link estimation," in *6th ACM Workshop on Hot Topics in Networks, HotNets 2007*, 2007.

[66] N. Patwari, J. N. Ash, S. Kyperountas, A. O. Hero, R. L. Moses, and N. S. Correal, "Locating the nodes: cooperative localization in wireless sensor networks," *IEEE Signal Processing Magazine*, vol. 22, no. 4, pp. 54–69, Jul. 2005, doi: 10.1109/MSP.2005.1458287.

[67] S. Adler, S. Pfeiffer, H. Will, T. Hillebrandt, and J. Schiller, "Measuring the distance between wireless sensor nodes with standard hardware," in *2012 9th Workshop on Positioning, Navigation and Communication*, Mar. 2012, pp. 114–119, doi: 10.1109/WPNC.2012.6268749.

[68] A. Parasuram, D. Culler, and R. Katz, "An analysis of the RPL routing standard for low power and lossy networks," *Technical Report No. UCB/EECS-2016-106*, p. 98, 2016.

[69] M. Bouaziz, A. Rachedi, A. Belghith, M. Berbineau, and S. Al-Ahmadi, "EMA-RPL: energy and mobility aware routing for the internet of mobile things," *Future Generation Computer Systems*, vol. 97, pp. 247–258, Aug. 2019, doi: 10.1016/j.future.2019.02.042.

[70] D. Vyas and R. Patel, "A survey: specific aspect of the RPL protocol and its enhancements," *International Journal of Intelligent Systems and Applications in Engineering*, vol. 12, no. 14, pp. 294–308, 2024.

BIOGRAPHIES OF AUTHORS

Ditixa Vyas received the B.Eng. degree in computer engineering from Dharmsinh Desai University, India, in 2005 and the M.Tech. degree in computer engineering from Charusat University, India, in 2013. Currently, she is pursuing her Ph.D. from Charusat University, India. Her research interests include the internet of things, computer networks, routing protocols, traffic engineering, cryptography, network security, and the analysis of algorithms. She has published more than 20 research papers in reputed journals and conferences. She can be contacted at email: ditixamehta@gmail.com.

Ritesh Patel received his doctorate degree in 2017 from Charusat University, India and received B.Tech. and M.Tech. degrees in 2002 from North Gujarat University, India and 2004 from DDU, India respectively. His area of interest includes cloud computing, internet of things, communication and networking, computer architecture, software engineering and cluster computing. He is the member of professional societies CSI, IETF. He is having 19+ years of teaching experience at UG level and concurrently 13+ years of teaching and research experience at PG level. He guided more than 40+ industry projects at graduate level and 25+ dissertations at post graduate level. He can be contacted at email: riteshpatel.ce@charusat.ac.in.