Load Balancing for RPL-Based Internet of Things: A Review

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Abstract

Low-Power and Lossy networks are an integral part of the IoT ecosystem. These networks are defined by their shared features such as having limited resources and high occurrence of packet loss. A routing protocol for such networks called Routing Protocol for Low-Power and Lossy Networks (RPL) was proposed in 2012. Even though RPL is now standardized and well-accepted by the community, it still has areas to be improved such as load balancing, stability, and support for mobility. This study focuses particularly on approaches proposed for the load balancing problem in RPL. In the literature, many researchers aimed to tackle this problem by creating different routing metrics that handle different objectives. This review makes a thorough assessment of these works, their strengths and shortcomings, and provides future directions on the issue.

Keywords: Internet of Things (IoT), Low-Power and Lossy Networks (LLN), Routing Protocol for LLNs (RPL), Routing, Load Balancing

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1. Introduction

Internet of Things (IoT), the system of interconnected and integrated devices with computing power, has become a popular and fast-growing concept in recent years. However, it is no longer just conceptual, IoT has started to be used in various areas ranging from smart homes and autonomous driving systems, to connected cities and smart grids. The number of IoT devices is expected to be around 75.44 billion by 2025, representing a five-fold increase over a 10-year period [1]. While nearly half of the connections between IoT devices are from home applications, connected work and connected city applications have shown an increasing trend in recent years [2].

As a large number of IoT devices have limited resources, studies proposed for such networks should take into consideration various constraints such as computing power, storage space, and energy. These types of network are referred to in the literature as Low-Power and Lossy Networks (LLNs) [3]. As LLNs constitute a large amount of IoT systems, devising improvements to their shortcomings is of paramount importance to both industry and academia. In this context, research has mainly focused upon improving stability and reducing the energy consumption of LLNs [4]. Routing Protocol for Low-Power and Lossy

Networks (RPL) is a well-accepted routing protocol for such resource-constrained devices [5] that aims to provide bidirectional connectivity between nodes within an LLN. Even though it is mainly proposed to provide multipoint-to-point (MP2P) communication, it also supports point-to-point (P2P) and point-to-multipoint (P2MP) network traffic.

While the research is in agreement that RPL has the potential to improve and thrive, it also has several shortcomings, such as a tendency towards load imbalance, a disregard for stability, and a lack of focus for mobility, all of which are in need of being addressed. These shortcomings prevent the widespread adoption of RPL as a routing standard, which is urgently needed as the number of IoT devices are projected to increase exponentially in the next decade [6].

In this survey, works found to improve load balancing in RPL are listed and examined. The works were selected through extensive Google Scholar searches, and also selected from the review of other surveys. As previously mentioned, only a few surveys [4][7] mention load balancing; however, unlike the current study, they have not rigorously focused on this issue.

The examined works were categorized by the methods used to improve load balancing, which range from the use of manual composite metrics based on well-known metrics such as ETX and hop count, or novel routing metrics to the utilization of heuristic methods. The current survey differs from others as it is based on a thorough evaluation of related works from the perspective of load balancing. For each main category, a tabulated view of the works is presented with a summarized main method, a list of the routing metrics used in the work, the work's advantages and shortcomings, details about the experimentation, and the work's methods of evaluation so as to provide readers with an in-depth evaluation. Previous surveys on RPL have tended to lack, or to only partially include, this type of information.

Furthermore, the strengths and weaknesses of these proposals are examined and future research directions on load balancing is suggested. The reviewed works were generally found to be unscalable and network/domain-specific, with a distinct lack of concern for mobility. Hand-created objective functions, parent selection algorithms (the algorithm that determines which parent node is a better candidate for routing for a given node), weights (to increase the importance of certain metrics for routing), and thresholds (used to limit changes in routes) all contribute to solving this problem.

1.1. Organization of the Work

This work is organized within seven sections. The current section briefly introduces the problem and the current survey. Section 2 summarizes the existing surveys on RPL in the literature, and outlines the main motivation behind the current survey. In Sections 3 and 4, general information is given on LLNs and RPL, each with their respective requirements and limitations. Section 5 explains the limitations of RPL, together with the concept of load balancing, and also mentions the potential problems that may occur within a load-imbalanced network. In Section 6, studies that focused on load balancing in RPL are explained and evaluated in detail, each with their respective contributions and shortcomings. Finally, Section 7 discusses the state of load balancing for RPL-based IoT, and summarizes the findings of the study. The structure of this survey study is outlined in Figure 1.

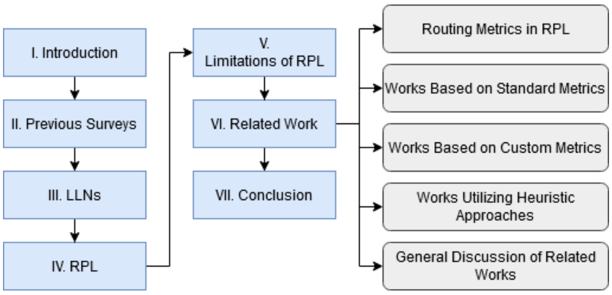

Figure 1: Organization of the survey

2. Previous Surveys on RPL

Among the many surveys that have been conducted on RPL, [4][8][9][10][7] stood out by either focusing on or just mentioning load balancing, and based on a systematic and detailed approach to reviewing studies on RPL. Moreover, they provide a guideline on reviewing and comparing the available research. Therefore, additional information about these surveys will be provided here since they have each taken load balancing into account.

In [4], a thorough analysis of LLNs and RPL was conducted, and their various limitations and drawbacks pointed out. Their survey reviewed 25 works that enhanced RPL in several different ways, such as modified or combined routing metrics, or enhanced routing methods. The survey pointed out the following areas of RPL as being in need of improvement in the future: downward traffic patterns, load balancing, metric composition, multiple-instance optimization, evaluation in real testbeds, and lack of applications in real-world scenarios.

In [8], 97 works that aimed to enhance RPL were reviewed. The reviewed works were categorized according to year of publication, the main areas of interest within RPL (upward/downward routing, load balancing, mobility, security, etc.), and their methods of evaluation (real experimentation or simulation). The high number of works reviewed is seen as an advantage to the paper, but it naturally came with a trade-off in terms of detail, such as how the proposed implementations worked, which routing metrics were utilized, and how the evaluations were conducted.

In [9], the usage scenarios and challenges of RPL were explained in detail and a systematic review of works that improve RPL presented. The reviewed works were grouped according to the main area of improvement, such as energy consumption, mobility, quality of service, congestion control, and security. Works that improved load balancing were also highlighted. A total of 57 works were reviewed and their main methods, advantages, and disadvantages summarized.

In [10], another comprehensive review of RPL was conducted that focused on objective functions. The survey consisted of 59 works, each grouped according to their main methods, such as works using single or composite metrics, multipath routing, or fuzzy logic. The survey included load balancing among the improvements identified in the reviewed works. The works were each reviewed and their main methods, improvements, shortcomings, and experimentations tabulated in detail.

In [7], a survey was conducted that primarily focused on load balancing schemes in RPL.

The survey started with an overview of RPL and current problems involving load balancing. A total of six problems were identified, including the "thundering herd" problem and the "hot-spot" problem. A total of 19 works were reviewed and then classified according to their main methods, and which of the six problems they solved.

While the previous surveys each focused on RPL, its key components, and its shortcomings, the issue of load balancing and related problems were not the main focus of these surveys, except for [7]. However, compared to [7], the current survey includes a higher number of reviewed works and a more systematic procedure of review. In this regard, the current work provides a more detailed definition of the issue of load balancing and its effects on RPL networks. The main objective of the current study is to analyze an often overlooked aspect of RPL, and to explore the promise of increased energy efficiency and performance in a more load-balanced network. A comparison of these prior surveys, accompanied by other well-known surveys [11][12][13] about RPL is presented in Table 1. For each survey, the table includes the publication date, the main subjects covered, and the number of works reviewed.

Table 1: General information about the previous surveys

Survey	**Publication Date**	**Subjects**	**Number of Evaluated Works**
[11]	2016	• RPL Features • Routing • Mobility • Review of RPL Enhancements	6
[12]	2016	• RPL Features • Problems Related to: – Traffic Patterns – Mobility – Resource Heterogeneity – Scalability – Reliability	None

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Survey	Publication Date	Subjects	Number of Evaluated Works
[13]	2017	• RPL Features • P2P-RPL Features • Energy Efficiency • Congestion Detection • Mobility Support	None
[8]	2017	• RPL Features • Review of the: – Upward & Downward Routing Enhancements – Multicast, Multi-Sink, Multi-Instance RPL Enhancements – Mobility Enhancements – Security Enhancements	97
[4]	2018	• RPL Features • Review of the: – Objective Function Enhancements – Routing Maintenance Enhancements – Downward Routes Enhancements	25

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Survey	Publication Date	Subjects	Number of Evaluated Works
[7]	2018	• RPL Features • Load Balancing • Problems related to Load Balancing • Review of the RPL Enhancements Focused on Load Balancing	19
[9]	2019	• RPL Features • Review of the: – Energy Consumption Enhancements – Mobility Enhancements – Quality of Service Enhancements – Congestion Control Enhancements – Security Enhancements	57
[10]	2020	• RPL Features • Objective Functions • Review of the: – Single & Composite Metrics Enhancements – Lexical & Additive Metric Composition Enhancements – Multipath Enhancements	59

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Survey	Publication Date	Subjects	Number of Evaluated Works
Our work	-	• RPL Features • Load Balancing • Problems related to Load Balancing • Detailed Review and Comparison of RPL Enhancements Focused on Load Balancing	35

3. Low-Power and Lossy Networks

Low-power and lossy networks (LLNs) consist of constrained nodes in terms of memory, power, and processing resources. Communication is also another constraint in such networks. Typical communication characteristics of LLNs are low data rates, limited frame sizes, high packet losses, limited ranges for communication, and dynamic network topologies [14]. LLNs are proposed to be used in different application domains such as smart homes and buildings, smart factories, smart cities, and in smart military solutions, all of which could have varying constraints and requirements in terms of energy usage, overhead, dependability, and performance [15][16].

An exemplar LLN network is given in Figure 2. Resource-constrained nodes in the network connect to the Internet through the LLN Border Router, which does not share the same resource constraints [17]. While each of the nodes in such networks can communicate with each other, traffic flow is generally from sensor nodes towards a sink node (LLN border router), as in typical data collection applications.

In order to ensure the effective and efficient usage of LLNs in IoT, several technologies and standards have been proposed and developed by both standardization bodies and researchers. To name a few, IETF 6TiSCH [18] is tasked with addressing problems in the MAC layer, while IEEE 802.15.4 [19] is concerned with the MAC layer and the physical layer of the protocol stack. 6LoWPAN [20] is a well-known standard that is tasked with providing adaptation between the IEEE 802.15.4 standard and the upper-layer protocols such as RPL or IPv6. Power-Line Communications (PLC) [21], blacktooth Low Energy (BLE) [22], and Wi-Fi HaLow [23] are some of the other technologies also utilized in LLNs.

3.1. Routing in LLNs

Different LLN characteristics should be considered whilst designing a suitable routing protocol for these networks. First, routing protocols for LLNs should be able to meet different characteristics for different application areas. Moreover, as nodes in LLNs are resource-

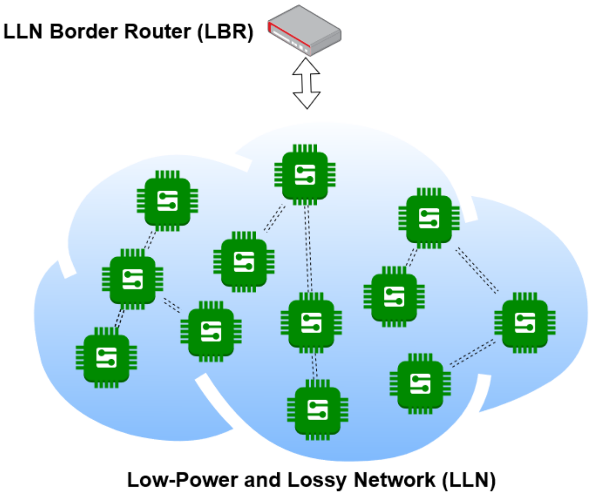

Figure 2: Representation of an LLN

constrained in general by nature, this creates numerous restrictions to the development of an efficient routing protocol. For instance, energy is one of the scarcest resources for nodes [24], which, therefore, should not be consumed by the frequent routing of control messages.

LLNs support different types of communication patterns. The most commonly used application is for multipoint-to-point (MP2P) traffic, in which sensor nodes are tasked with gathering and reporting data to a sink node or LBR (LLN Border Router). The communication could also be downward, from the LBR node to sensor nodes, as in Point-to-Multipoint (P2MP) traffic.

Lastly, Point-to-Point (P2P) traffic provides direct communication among the sensor nodes. Different requirements such as centralized or distributed topology, security needs, and mobility create a need for different patterns of communication in LLNs. This adds a level of complexity in designing efficient routing protocols for LLNs [25][26].

Three data exchange models typically exist in LLN sensor-based applications: event-based, time-based, and query-based [15]. In event-based models, sensor nodes report their findings when they detect any notable change in their area of responsibility. In time-based models, the sensor nodes report their findings at regular intervals or at a set time. In query-based models, the findings of sensor nodes are reported when a specific query is received by the nodes. However, these data exchange models can be merged, resulting in hybrid models as well. The chosen data exchange model is, therefore, closely linked to the nodes' energy consumption, hence the stability of routing paths in the network can affect the frequency of route updates.

As links are unreliable and lossy in LLNs, route updates can never be guaranteed to reach their destination nodes [27][28], and the rate of packet loss is generally unpredictable in LLNs. A link can present varying data loss rates at different times, owing to aspects such as hidden terminal problems, receiver collisions, or RF interference of nodes [27]. Nevertheless, statistical data based on earlier deployments could help to predict a reasonable rate of packet loss [27]. To summarize, a routing protocol for LLNs must have the capability to work within the aforementioned unreliable link conditions.

Even though sensor nodes are expected to be immobile in most of the scenarios, real life cases and future projections differ in the way that an extensive number of nodes will be mobile [29][30]. For example, nodes in healthcare applications responsible for collecting data from people are inherently mobile [31]. Hence, mobility is one of the important constraints of a prospective routing algorithm. Last but not least, a suitable protocol for LLNs should be able to scalable since they are envisioned with the fact that they could handle different topologies from several nodes to thousand in different application domains such as home [32], urban [30] and industrial [29].

4. Routing Protocol for Low-Power and Lossy Networks (RPL)

Tasked by the IETF, the ROLL group published an RFC for RPL in 2012 [33]. Since then, the group has published further RFCs, which detail the main components of RPL, namely routing metrics [34], Trickle timer [35], and objective function [36][37]. In this section, the basic operations and the main components of RPL are explained in detail.

RPL is a proactive distance-vector and source routing protocol. It builds Directed Acyclic Graphs to represent the network topology. Each DAG associated with a single root destination is known as the Destination Oriented DAG (DODAG) in RPL terminology. A network could have multiple DODAGs and multiple instances. Single or multiple DODAGs sharing the same objective function is known as an RPL instance [14]. The objective function determines the route selection. Therefore, RPL instances play a key role in providing different routes even for the same destination with different objectives such as minimizing energy, ETX, or latency. Whilst a node could be a part of several DODAGs in different instances, it can only join a single DODAG (root) in one RPL instance. A sample RPL network with a single DODAG is illustrated in Figure 3.

In an RPL network, the nodes are separated into three groups: hosts, routers, and LBRs (LLN Border Routers) [14]. Hosts are the nodes that can create data traffic but are unable to forward it, whilst routers are nodes that are capable of both. Lastly, LBRs are the roots of a DODAG and can also be described as a collection point for network traffic. LBRs can construct a DAG and can act as the edge routers between the LLN and the Internet [38]. A single DODAG could have multiple LBRs.

4.1. Construction of DODAG

RPL is mainly proposed for MP2P traffic by discovering upward routes towards the root of a DODAG. However, it also supports P2P and P2MP traffics by constructing downward routes. It has four main types of messages to construct the network topology and to discover routes. These message types, which are defined in the ICMPv6 protocol, are as follows: DODAG Information Object (DIO), DODAG Information Solicitation (DIS), Destination Advertisement Object (DAO), and Destination Advertisement Acknowledgement (DAO ACK). First, the DODAG root transmits DIO messages in order to create routes in an upward direction (from children to root). Then, children nodes transmit unicast DAO messages to the DODAG root for reverse-route construction.

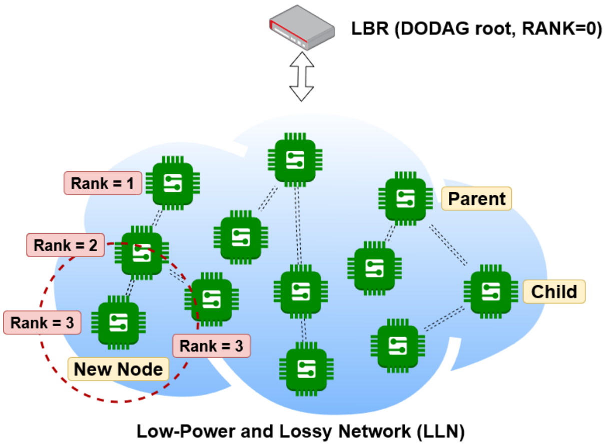

Figure 3: Representation of RPL with a single DODAG

DIS messages are sent when a new node joins the network. The node asks for topology information from its neighbors in order to join the DODAG. DIO messages are typically broadcast messages sent from the root to its children based on the Trickle timer. However, they could also be sent upon request with the receiving of a DIS message. In a DIO message, a node advertises its rank and the objective function to be used. Rank represents the position of a node with respect to the root node. The objective function computes the rank of a node based on routing metrics and optimization objectives. For instance, OF0 [36], which selects the node nearest to the DODAG root as the preferred parent, is one of the default objective functions for RPL routers.

Rank increases in the downward direction of the DODAG and decreases in the upward direction. The fact that the rank of a parent node should be lower than its children nodes prevents routing loops from occurring in the network. When a node receives a DIO message, it updates its parent candidate set and chooses a parent based on the rank values of the nodes in this set. It then calculates its rank value. If the calculated rank is found to be higher than its parents (i.e., the node is on a downward route from the parents), the DIO message is updated with the new rank information. Finally, it forwards the DIO message to its neighbor nodes. As a result, each node in the network builds its upward routes by using DIO messages.

DAO messages enable a node to transmit its target information upwards through the DODAG, allowing for downward route construction between the DODAG root and the associated nodes [14].

These messages are sent by every node in a DODAG (except the root) in order to generate the routing tables with child prefixes, and to advertise these addresses and prefixes to their parents. Two separate modes are specified by RPL for the maintenance of downward routes within each instance: storing and non-storing. In the storing mode, when a parent node receives a DAO message from its children, the node saves the destination prefix and the address of the message sender as the next hop in its routing table, and then subsequently forwards it to the selected parent. In the non-storing mode, again a node transmits the received DAO message to its selected parent; however, no other routing information is stored. DAO-ACK messages are optional unicast messages that are transmitted upon request to the sender to acknowledge delivery of the DAO message [14].

While DIO and DAO messages are employed for the discovery of upward and downward routes, respectively, RPL also provides P2P communication in the following way. First, the nodes send their messages to the root in the upward direction, then the root node forwards these messages to the destination node in the downward direction. If an intermediary node knows a route to the destination, this node could also forward the packets to the destination by preventing packets from unnecessarily traveling until the root node.

Similar to IP fragmentation, RPL also fragments its messages into smaller packets. As these messages can be loaded with several optional parameters and information, the fragmentation tends to divide the message into several packets. Loss of one fragmented packet means the loss of the whole message, which then incurs the increased cost of retransmission and an associated increase in energy consumption.

4.2. Trickle Timer

The sending rate of DIO messages is governed by the Trickle timer. When a fluctuation in routing information or inconsistency is detected, Trickle timer increases the rate of transmission, aiming to re-circulate up-to-the-minute information. When the network approaches stabilization, the Trickle timer reduces the rate of transmission exponentially, to restrain the number of transmissions as there is nothing new to broadcast. Also, when a node detects that its neighbors are broadcasting the same control packet it intends to transmit, the node suppresses the transmission to reduce redundancy in the network. The Trickle algorithm is specified in RFC 6206 [35].

The Trickle algorithm utilizes four separate values, where I is the current interval size in milliseconds, which sets the running time of the algorithm and it is incremented in real-time; k is an integer used as a redundancy constant; t denotes a time within the current interval; and, c is the counter value. Transmission can be labeled as consistent or inconsistent, based on the implementation. First, the algorithm selects an I value between the pre-specified *Imin* and *Imax* values. In the second step, c is set to zero and t is randomly set between $I/2$ and I. Trickle starts listening and if a "consistent" transmission is heard, the c value is then incremented. Trickle only allows a transmission when c is less than the redundancy constant k, meaning that a certain time should pass before making another transmission. This step is referred to as the suppression mechanism of the Trickle algorithm. When I reaches *Imax*, the algorithm doubles the interval length and starts over. If Trickle hears a transmission as "inconsistent" and I is greater then *Imin*, the timer resets by setting I to *Imin* and the algorithm continues from the second step. The meanings of the terms consistent and inconsistent are dependent on the application that uses Trickle.

4.3. Objective Functions

Two standard objective functions are proposed for RPL: Objective Function Zero (OF0) [36] and Minimum Rank with Hysteresis Objective Function (MRHOF) [37].

OF0 works by selecting the node nearest to the DODAG root as the preferred parent, while completely disregarding load balancing. Additionally, one more parent is selected as an alternate in the event of a loss of connectivity with the preferred parent.

MRHOF is devised to avoid incessant changes in preferred parents, which reduces the stability of a network. MRHOF works by calculating the cost of a path for passing among the neighboring nodes that form a path between the origin and destination nodes. The calculation is performed by adding two values; the cost of the prospective neighbor node's or link's metric, and the cost of the metric broadcast in the transmitted message. Following this calculation, the preferred parent is selected from the node with the lowest path cost.

4.4. Repair Mechanism

Version number represents the version of the DODAG formed, and is incremented by the root each time a new DODAG is formed. This is the approach taken by the global repair mechanism for the maintenance of a DODAG. However, in order to avoid the costly reconstruction process of DODAG, two local mechanisms are also introduced in RPL. In the case of unavailability of the selected parent node, nodes either choose an alternate parent or use a neighbor with the same rank to transmit its messages to the root node.

5. Limitations, Drawbacks, and Open Challenges of RPL

While introduced as the standard routing protocol of LLNs, RPL suffers from several limitations as evidenced in a plethora of recent studies [4][8][9][10]. Load imbalance can be considered as one of RPL's weaknesses, as in real life, largescale LLNs are almost always distributed in a non-uniform way [39]. A sample load-imbalanced network topology can be observed in Figure 4.

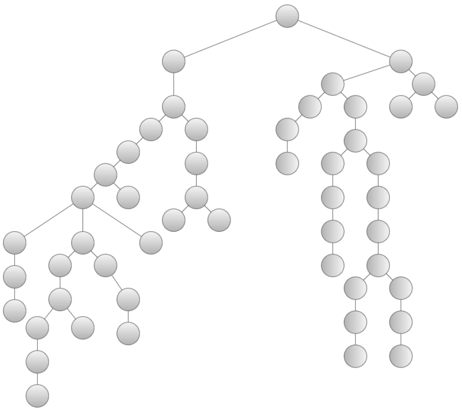

Figure 4: Load-imbalanced network topology

Load imbalance in a network may occur due to several different reasons. The hot-spot problem [40] is one such cause. This problem occurs when the parent node or a node forwarding a message is faced with network congestion, which urges this node to use its resources in order to handle excessive message traffic. Hot-spots occur more frequently if a node is situated near the root. This problem ends up causing depletion of that node and system resources, and thereby reduces the network lifetime.

In [41], the authors identified two further problems that can lead to load imbalance. The first problem is called “thundering herd,” which occurs when a node joins the RPL-based network with a better transmission path. This may trigger changes in a large number of sub-nodes, potentially impacting upon the network’s stability. The second problem, named “randomly unbalanced network,” occurs if two parent candidates happen to have the same rank value, which then leads to random selection of the parent. This practice has the potential to cause load imbalance purely by chance.

The following subsections will explain other limitations, drawbacks, and open challenges of the main components and factors of RPL in more detail, as well as their relation to the issue of load balancing.

5.1. Energy Consumption

Considering the limited resources of the nodes in an LLN, energy consumption can be seen as among the main constraints when designing an efficient routing algorithm. Hence, reducing energy consumption and having a high network lifetime is generally the main goal of any research aimed at improving RPL. By design, RPL aims to decrease energy consumption with the help of Trickle timer. However, according to [42], the efficiency of Trickle timer in mobile environments decreases. Energy consumption is clearly linked with load balancing, and a load-imbalanced network would certainly lead to increased energy consumption.

5.2. Reliability

Reliability in the context of RPL is evaluated by the number of lost packets and the average delay of transmitting packets between end-points. As a rule of thumb, increased reliability comes at the cost of higher energy consumption, generally in the form of retransmissions or acknowledgements. Thus, finding a good balance is one of the goals of RPL enhancement. Load imbalance may also lead to a lack of network reliability.

5.3. Congestion

Similar to real-life examples, network congestion is one the main reasons behind increased energy consumption, increased delay, and decreased reliability in LLNs [43]. Congestion and load balancing are also related concepts, as a load-imbalanced network will certainly lead to congestion at some point.

5.4. Objective Function

One of the main limitations of the parent selection mechanism in RPL is to use the same parent each time when forwarding a packet towards the root. Since this single-path forwarding disregards the load balancing factor [44], it would lead to power drainage or the demise of overloaded parent nodes, resulting in potential disconnections within the network.

RPL supports the use of both single and multiple routing metrics. In the use of a single metric, whilst the metric satisfies one criterion, it could lead to other inefficiencies within the network. For instance, whilst the expected transmission count (ETX) metric enables

RPL to choose the most dependable path [45], it might also cause early partitioning of the network due to the absence of any load-balancing mechanism, which would prevent energy-constrained nodes from depleting their power. Therefore, the proposals put forth in the literature for the improvement of load balancing tend to utilize multiple metrics. However, the use of multiple metrics is not specified in the RFC, except for multiple instances [46], in which separate instances with separate routing objectives are used with different routing metrics in order to achieve those objectives.

Lastly, in RPL, the cost of routing a path is calculated by combining the costs of the links that constitute the path. This leads to situations where a path that consists of a high number of hops would seem to have a higher cost when compared to a path with fewer hops, while the former path may have links that are of a higher quality [47]. When making routing decisions, this may cause the protocol to choose routes that are seemingly low-cost, but consist of lower quality links [47].

5.5. Mobility

While RPL was not designed with mobility in mind, real-life applications could include mobile nodes. However, in its current form, RPL fails to differentiate between mobile and non-mobile nodes; hence, it has limited adaptability to dynamic networks [48]. For instance, if a mobile parent leaves the network, that may cause sudden packet loss within the network, as the child nodes may not know that their preferred parent has left the topology. The Trickle timer itself has also some issues with mobility, as it could give a slow response to a fast-changing mobile network, or equally not give any response at all at the right time [48]. RPL could be configured to accommodate mobility requirements such as locating mobile nodes in leaves or setting Trickle timers to frequently send control messages; however, these types of solution may end up creating large volumes of routing control message traffic [48].

5.6. Stability

The stability could refer to two different meanings in RPL jargon: route stability and node stability. Route stability is related to the validity duration of a routing path. Since mobility is generally discarded in the literature, most studies refer simply to node stability, in other words, the validity duration of the preferred parents [49]. Please note that node stability and route stability are highly correlated concepts, since the depletion of a node could result in route changes. In general, low stability causes higher overhead and higher energy consumption in the network. The current solutions that attempt to handle load balancing in RPL generally cause instability in the network, which is of course an undesired side effect [50].

Hence, a good solution must take stability, and as real-world conditions dictate, mobility into account as well. Invariably, the solutions utilize parent selection mechanisms or multipath routing in order to balance the load and to improve RPL performance in general. Due to the frequent changing of parents, high stability might not always be achieved, and striking a balance between stability and load balancing can be considered the more realistic goal.

Stability can be measured node-wise by calculating the occurrence of control messages such as DIO, DAO, and DIS messages that pass through the node [51]. This, however, does not always imply low stability, as nodes with a higher number of children will generally experience a high number of messages passing through. Another popular method of measurement is to calculate the ratio using the same transmission route between two nodes [51][52].

5.7. Security

Security is handled in three basic modes in RPL, according to the RFC 6550 [33]: unsecured, pre-installed, and authenticated. The unsecured mode, as its name suggests does not involve any security measures in the control messages. In the pre-installed mode, RPL uses secure messages. A node uses a pre-installed key to join the network and to ensure message confidentiality, integrity, and authenticity (CIA). In the authenticated mode, nodes that joined the network with a pre-installed key are only able to act as hosts (leaf nodes). A key authority that assigns a second key to a node is required in order for that node to become a router (parent).

Although RPL has certain countermeasures against external attackers, it is still vulnerable to attacks from inside. Attacks against RPL are covered in three groups in [53]: attacks against resources, attacks on topology, and attacks on traffic. While attacks against resources aim to deplete the resources of nodes in the network by causing unnecessary operations, attacks on topology affect the construction of RPL topology in a non-optimal way or lead to the isolation of some nodes from the topology. Finally, attacks on traffic analyze network traffic in order to implement more complex attacks. Therefore, researchers focus on improving RPL security and these approaches can be covered under two broad categories: secure protocol-based defense mechanisms, and intrusion detection [54].

A load-imbalanced network could decrease the resilience of a network against certain attacks such as those that target resources or the topology. For instance, if an attacker achieves the formation of a load-imbalanced network, they could easily manage the consumption of network resources or the isolation of some nodes from the network. Therefore, load imbalancing is also an important issue from a security perspective. It is assumed that the reviewed works in this survey each use the unsecured mode in their methods, unless specified explicitly. As none of the works in this survey mentioned any type of RPL security (either pre-installed or authenticated), it can be said that security was not the primary concern of the researchers when designing and implementing their enhancements.

6. Related Work on Load Balancing

There are a good number of proposals in the literature that aim to improve RPL. Considering the imbalance-prone nature of RPL, and the adverse effects of such imbalanced networks in routing, research on improving load balancing has been a popular research topic in IoT routing. This current study provides a thorough evaluation of the studies in the literature considered most important that have focused on load balancing in RPL.

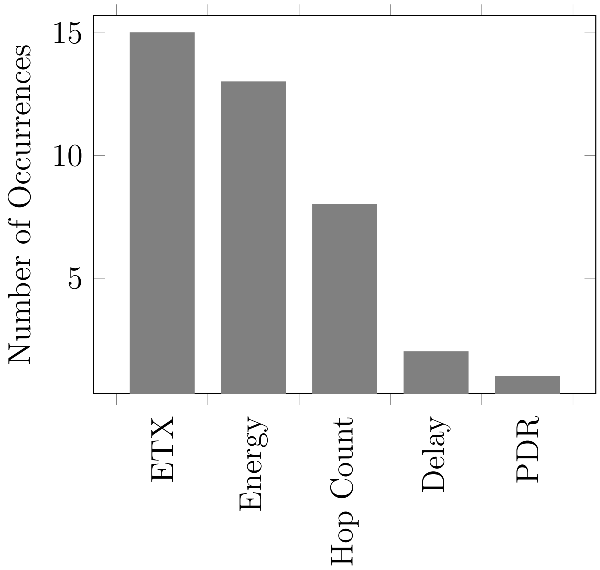

Figure 5: Distribution of standard RPL routing metrics used in metric-based works

It should be noted that while most of the reviewed works explicitly state load balancing as their focus of improvement, some of the works use the term energy (or residual energy) balancing. These works are also considered as improving load balancing in RPL.

The related studies are classified into two groups: studies that utilize routing metrics and objective functions to improve load balancing, and works based on heuristic approaches. Additionally, the first group is further divided into two sub-groups, as studies based on: standard metrics, or custom metrics. The metric-based methods also differ in their methods of routing: using novel or edited parent selection algorithms, or utilizing multipath routing (routing over numerous alternative paths through the network).

The proposed metrics could have different characteristics. They could be node-based or link-based, depending on where the metric is acquired from the network. The purpose and usage of the metrics determines its category. Energy, hop count, and delay are some of the node-based metrics, whilst metrics concerned with the general transmission quality are link-based.

Furthermore, they could be lexical or additive, which determines in what manner the metrics are compared with each other. A metric used lexically is part of a basic values comparison, whilst a metric used additively is combined with different (optionally-weighted) metrics in order to make a more nuanced comparison. Lastly, metrics could be atomic or composite, based on the number of metrics included; however, all of the metrics proposed for load balancing in RPL are composite.

6.1. Routing Metrics in RPL

In this section, well-known, standard routing metrics used in RPL and specified in RFC 6551 [34] are briefly described.

The *Node State and Attribute (NSA)* metric carries data about a node's characteristics, such as the A and O flags. The A flag is the aggregation attribute, which can be used to increase battery life in suitable environments, whist the O flag indicates whether a node is overloaded or available to process traffic.

The *Node Energy* or energy consumption metric provides information about a node's energy. It can be used either as a metric or a constraint. A derivative of this metric is the *Estimated Energy* or remaining/residual energy, which is the percentage of a node's residual energy. In the context of load balancing, having similar residual energy among nodes in the network would indicate a load that is better balanced; however, residual energy is utilized less than energy consumption.

Hop Count (HC) is the metric which records the number of nodes traversed along a path from the source node itself to a destination.

Throughput metric is simply the number of messages that pass through a node.

Latency is a metric that is concerned with the measurement of the time it takes to deliver a message from the source node to the destination node. Similar to Energy, it can be used either as a metric or a constraint.

Packet Delivery Ratio (PDR) represents the ratio of successfully delivered packets to the total number of sent packets in the network. Simply, PDR is a metric that measures the successful transmission of packets in the network.

Link Quality Level (LQL) quantifies the reliability of a link using a value that ranges from 0 to 7, with 0 denoting an unknown quality level and 1 denoting a high-quality link. However, exactly how this value is calculated varies according to the implementation.

Expected number of Transmissions (ETX) is a metric that holds the number of transmissions expected to be made from a node to a given destination. The computation of ETX itself is also implementation-specific. ETX can also be used either as a constraint or a metric.

Link Color (LC) is a versatile metric whose value can be used to attract or avoid links for specific types of traffic. For example, the LC metric can specify parent selection based on rules defined by the user, such as selecting parents that are fulfilling certain requirements.

A comparison of the metrics used in the works is illustrated in Figure 5. The figure shows that ETX and Residual Energy are the most used metrics in the literature. ETX is frequently used as a metric in order to ensure the transmission of messages uses high quality routes with a low number of retransmissions, and Residual Energy is used frequently in order to keep the energy levels in consideration. The energy metric in the figure contains two metrics related to energy: energy consumption and residual energy. The two metrics complement each other as they effectively measure two sides of the same value. However, most studies ($\approx 75\%$) in this category use residual energy, while the others use energy consumption.

6.2. Related Studies based on Standard Metrics

This section covers studies based on standard metrics. As previously pointed out, all of the reviewed works utilized multiple metrics in their methods.

In [55], the authors proposed a strategy for routing in RPL that utilizes mobile sinks. In the work, three metrics are used to calculate node weight: residual energy, number of hops, and number of neighbors. The weight of the metrics themselves are based on coefficients as given in Equation 1: with β used to weigh residual energy and number of hops, and γ used to assess the number of neighbors. However, the suggested values of the weights were not specified in the study. These weights were introduced in order to reduce the scaling effect, which is caused by different units of measurement. The node with the largest weight value is then selected and the sink is physically moved towards that node, resulting in better load balancing in the network. However, the work tended to have a high message overhead, and its performance in real-life scenarios remains unclear.

$$\omega_i = \beta h_i^k e_i + \gamma b_i \tag{1}$$

In [56], the authors proposed a new metric named PFI (Packet Forwarding Index) and combined it with other metrics such as hop count and energy. PFI is a novel metric that is the logarithmic product of the success rate of packet deliveries. The combinations are performed lexically and additively for the optimization of various aspects of performance, such as shorter path construction and the bypassing of unreliable or malicious nodes.

Two combinations of metrics were proposed. The first combines hop count with PFI, while the second combines hop count with residual energy. The combinations are calculated both additively and lexically, and two different weight parameters are also included in the additive combination function. Different sets of weights are then used in the evaluation phase.

The results showed that the combined metrics enabled better discovery and avoidance of malicious or unreliable nodes, while having proportionate latency and better distribution of energy consumption to nodes on the path compared to single metrics being used. Moreover, while the first combination improves on PDR, the second results in a reduction in energy consumption.

In [57], a composite metric named L^{2}AM (Lifetime and Latency Aggregatable Metric) was proposed that considers energy and reliability constraints in two parts. First, an energy consumption balance is aimed to be created so that each node consumes approximately the same amount of energy, thus prolonging the overall network lifetime. A new metric named FSELC (Fully Simplified Exponential Lifetime Cost) was implemented which combines transmission power and residual energy metrics (both utilized as ratios) in an additive manner in order to guide parent selection by discouraging high energy-consuming routes. FSELC is presented in Equation 2, where E_{batt} and P_{tx} values are residual energy and transmission power, respectively. In the second part, data reliability along the paths is taken into account, using the well-known Expected Transmission Count (ETX). The FSELC value calculated in the first part is then combined with ETX in order to produce the composite L^{2}AM metric, as shown in Equation 3. The effectiveness of the proposed metric was backed up with simulated results. While an increase in the network lifetime (residual energy) compared to the standard ETX metric was observed, the claimed increase in reliability was not seen as having been fully justified.

$$FSELC(P_{tx\%}, E_{batt\%}) = 2^{P_{tx\%} \div E_{batt\%}{}^{T}} \tag{2}$$

$$L^2AM = ETX \times FSELC(P_{tx\%}, E_{batt\%}) \tag{3}$$

Another work that combined different types of metrics such as ETX, residual energy, availability information, affordable workload, and robustness of hardware was proposed in [58]. The metrics were combined for the objective function named SCAOF (Scalable Context Aware Objective Function). Among the metrics used in SCAOF, availability information represents the DODAG paths associated with data that is of interest to the application (sensor data etc.). The affordable workload can be summarized as a node's inclination to use its energy, and the robustness of hardware as the number of restarts that occurred since the system startup. These three metrics make up a sub-composite metric named Link color. Link color is combined with weighted (α_1 and α_2 respectively) ETX and Residual Energy metrics, resulting in the SCAOF composite metric, as shown in Equation 4. The α_1 and α_2 weights are set as 0.4-0.6 and 0.3-0.7 in the evaluations, respectively. The experimental results show that combining these metrics results in a routing scheme that selects paths that are more reliable and do not contain nodes that drain their power supply.

$$\begin{aligned} rank(n,p) = rank(p, p_{pref}(p)) + LinkColor + \\ (\alpha_1 ETX(n,p) + \alpha_2 RE(n,p)) \end{aligned} \tag{4}$$

A new objective function based on energy was proposed in [59]. The function uses the nodal residual energy metric, which is introduced as the ratio of available and residual energy of a node, in the parent selection mechanism. The energy levels are calculated by polling the nodes in the network to check their battery voltages. The proposed OF combines the Hop Count and ETX metrics with the residual energy metric. A threshold value (5%) is also set for parent changing, meaning a new parent is selected only if the residual energy difference exceeds 5%. The implementation of a threshold aims to reduce frequent changes in the network to improve stability. The results show that their OF proposal has increased the network lifetime by up to 40% in comparison to the default OFs of RPL, OF0, and MRHOF. However, notably, the proposed OF itself was not specified in any detail.

In [60], a novel objective function named ALABAMO (A Load Balancing Model for RPL) was proposed. As the name suggests, the main objective of ALABAMO is to improve load balancing. It is based on RPL's MRHOF with the addition of composite metrics such as maximum workload ratio and the maximum ETX ratio. The maximum workload is calculated as the ratio of sent packets of one possible parent of a node to another, and similarly, the maximum ETX ratio is calculated as the ratio of ETX values of one possible parent of a node to another. These metrics are presented according to Equations 5 and 6, respectively, where SP denotes the number of sent packets and o denotes an offset value. The parent selection is based on path calculations and a comparison of the aforementioned metrics. The experimental results show that the network lifetime has a twofold increase when compared to the default RPL implementation. ALABAMO has also been shown to reduce the standard deviation of energy consumption by 50.64%, which indicates that nodes expend energy homogeneously, thus extending the lifetime of most nodes in the network.

$$ETX_{ratio} = \begin{cases} \frac{ETX_{p2}}{ETX_{p1}} * 100 & ETX_{p1} \geq ETX_{p2} \\ \frac{ETX_{p1}}{ETX_{p2}} * 100 & \text{otherwise} \end{cases} \tag{5}$$

$$Workload_{ratio} = \begin{cases} \frac{SP_{p2}+o}{SP_{p1}+o} * 100 & SP_{p1} \geq SP_{p2} \\ \frac{SP_{p1}+o}{SP_{p2}+o} * 100 & \text{otherwise} \end{cases} \tag{6}$$

In [61], a new scheme named CA-RPL (Congestion Avoidance RPL) was proposed. CA RPL is a multipath routing protocol that utilizes a composite metric named $DELAY\_ROOT$ in order to handle network congestion and load-balancing problems. $DELAY\_ROOT$ is a function of four routing metrics: average delay towards the DAG root, rank, ETX, and the number of packets. The function's formula is presented in Equation 7, where REC_v is the number of packets a node v receives, and the weights of a, b, c, and d are set to 10, 10, 2, and 10, respectively. The γ value is set to 100,000. The average delay towards the DAG root is itself a composite metric, shortened as Minimized Delay Metric, and can be defined as the sum of the forwarding delays along the path between a node and the DAG root. The study's results showed that CA-RPL produced better load balancing in the network, accompanied by a 30% and 20% reduction in average delays and packet loss ratio, respectively. The authors cited the energy consumption improvement and handling mobility as their future goals.

$$W = \frac{\gamma}{a * ETX_{u,v} + b * REC_v + c * RANK_v + d * DELAY\_ROOT_{u,v}} \tag{7}$$

In In [62], an adaptive and distributed control mechanism named PC-RPL (Power Controlled RPL) was proposed. PC-RPL can be considered as an improvement upon QU-RPL [50], by further aiming to mitigate load imbalance and the hidden terminal problem of its predecessor. *Hidden Terminal problem* [63] occurs where nodes can communicate with a wireless access point, but cannot communicate with each other, resulting in decreased performance in terms of energy efficiency and latency. An adaptive and distributed control mechanism is developed in which routing topology and transmission power of nodes are controlled jointly. Combined ETX, Hop Count, and RSSI (receive signal strength indicator) metrics are used for parent selection, which is similar to RPL in terms of metrics used (ETX and HOP count). The RSSI value calculates the transmission power required to transmit a message to the neighbors of a node, where a lower value is more preferable. RSSI is obtained by making nodes transmit DIO messages with a maximum transmission power to seek greater link connectivity. The authors claimed PC-RPL to be successful in alleviating the hidden terminal problem experienced in QU-RPL. A sevenfold reduction in packet losses, accompanied by a 17% improvement in aggregate bandwidth was achieved. However, the method of calculating RSSI may lead to an increase in energy consumption.

In [64], the authors proposed a novel OF for RPL, which employed a composite metric consisting of Hop Count and ETX metrics. To increase routing stability and reduce frequent parent changes, two separate thresholds for the two metrics were also introduced, which can be observed in Equations 8 and 9. In Equation 8, σ_{pf} denotes the sum of the standard deviation of transmission attempts per packet, while θ is the threshold value. In Equation 9, $\hbar_{pf}$ denotes the difference of the number of hops between the current parent and a candidate parent, while δ is the threshold value. After the calculation of these thresholds, the values are used for comparison in the parent selection algorithm. The parent selection algorithm compares ETX and Hop Count metrics of parent candidates with the added custom thresholds in order to find the best candidate. The experiments that the authors conducted with these thresholds resulted in increased stability, reduced control message numbers (due to the lack of parent changes), and decreased energy consumption among nodes. On the other hand, the PDR of the proposed approach was found to be lower than the standard ETX. It should be noted here that the evaluations were conducted with only 20 nodes and within a simulated environment, which could raise questions regarding the scalability of the approach.

$$Link\ Metric\ Threshold: \alpha = \sigma_{pf} + \theta \tag{8}$$

$$Hop\ Metric\ Threshold: \beta = \hbar_{pf} x \delta \tag{9}$$

In [65], an enhancement over RPL named EL-RPL (Energy and Load Aware RPL) was proposed, which combines three separate metrics: ETX, current load, and BDI (battery depletion index) for the parent selection mechanism. The current load calculation is based on the number of children a parent node has, whilst the BDI value is the ratio of initial and residual energy levels of a node. These metrics are then combined in an OF named OF-EL, with differing weights. The route with the lowest OF-EL value is then selected as the optimal path. The results of EL-RPL showed a 4% increase in PDR, as well as a 10% increase in the network lifetime compared to the baseline methods. However, these evaluations were conducted with a low number of nodes (30).

In [66], a traffic-aware, load-balancing scheme with a composite metric named ETXPC RPL was proposed. The composite metric is the ratio of aggregated parent count to ETX. The load balancing algorithm of ETXPC-RPL utilizes the composite metric for parent selection, with parents with fewer children and a lower ETX being stronger contenders for selection. As can be seen from the simulation results, the proposed load-balancing approach showed an improved packet delivery ratio with less power consumption.

The following works differ from those mentioned so far based on their method of routing. Instead of novel or enhanced parent selection algorithms, the following works utilize multipath routing.

In [52], a multipath routing scheme was proposed in which traffic is forwarded probabilistically to several parents in order to reduce energy consumption and to improve load balancing. An expected lifetime metric (ELT) was proposed for the broadcasting distribution among the nodes. This metric is calculated according to several steps. The first step involves computing the traffic to transmit ($\mathrm{T_N}$) value of a node. Then, the ($\mathrm{T_N}$) value is combined with the ETX metric, and divided by the data rate in order to produce a transmission ratio value. In the final phase, ELT is calculated by dividing the transmission ratio value calculated in the previous step with the residual energy metric. The result of this division is combined with the transmission power metric in order to calculate the energy required for transmission of all traffic. The whole process is as shown in Equation 10.

$$ELT(N) = \frac{\mathbf{E_{res}(N)}}{\frac{T_N \times \sum_{P \in Parents(N)} \times ETX(N,P)}{DATA\_RATE}} \times \mathbf{P_{TX}(N)} \tag{10}$$

In the proposed scheme, nodes susceptible to bottlenecks are identified based on the ELT values. The parent selection phase takes the node's lifetime and the lifetime of the suspected bottlenecks into consideration, making a list of parents with the highest ELT values ranked lower than the node itself. Then, these nodes are considered in constructing a balanced topology with multiple parents. Load balancing in the network is then ensured by distributing the load to each parent that a node has.

Using ELT values of the parent nodes and the weight of the traffic that is to be sent, the parent is then selected. The experimental results showed improvements in the network lifetime and load balancing. However, the work could be said to carry the risk of fragmentation, and the solution must therefore be improved in order to handle that. In an extended study [67], the instabilities and convergence problems were notably addressed.

In [68], another multipath extension to RPL, named M-RPL (Multipath RPL), aims to provide temporary multipath routing to alleviate network congestion. The implementation of M-RPL is divided into two parts: congestion detection, and congestion avoidance. The congestion detection algorithm utilizes the PDR metric in order to make comparisons and find out whether or not a given route is congested. A congestion interval (CI) value is also used so as to avoid too many messages being present in the network. If congestion is detected in a route, the congestion mitigation phase starts, in which a node's forwarding rate to the congested node is reduced and the traffic is forwarded to alternate paths. The experimental results for M-RPL showed that when compared to the standard RPL, the use of M-RPL reduced congestion and increased the overall throughput at the expense of additional overhead. However, it should be noted that the experiments were conducted with a very low number of nodes, as shown in Table 4.

In [69], an adaptive multipath energy-balancing scheme was proposed. This scheme is based on a novel metric named energy dispersion (*ED*) which is used to calculate the residual energy of a possible parent and the other nodes in this possible parent's vicinity. *ED* is used to determine how balanced (in terms of energy) a node and its environment is. The multipath scheme uses this *ED* value to handle routing through the network greedily. Multipath routing is thereby utilized in order to handle different network requirements such as better energy balance or lower packet delay. The results obtained in the work indicated that better energy balancing was achieved, as well as higher stability and lower delay. On the other hand, the multipath scheme's greedy manner resulted in bottlenecks in routing, especially in tests conducted using larger-sized networks.

The studies covered in this section are outlined in Table 2. To summarize, most of these studies utilized ETX in some manner in their methods. Energy consumption is another popular metric that has also been used in the proposals. Most of the studies reported improvements in PDR and energy consumption, while others reported improvements in delay or balance. On the other hand, most of the studies were tested using simulated networks with a low number of nodes, and some [52][58][66] carried a risk of fragmentation or high overhead.

Table 2: General information about the evaluated works that are based on standard metrics.

Name	**Main Method**	**Metrics & Usage**	**Advantages**	**Shortcomings**	**Real / Simulator & # of Nodes**	**Evaluation Metrics**
Mobile Sinks [55]	• Moves sink nodes towards leaves by combining metrics such as residual energy, neighbor count and hop count • Parent Selection	• Residual Energy (L) • Hop Count (A) • Number of Neighbors* (L)	Increased network lifetime and traffic balance	Generates high message overhead, performance unclear in real-life scenarios	WSNet - 1600	Network Lifetime, Residual Energy, Packet Overhead
Composite routing Metrics for RPL [56]	• Among three metrics, two are combined in lexical and additive manners • Parent Selection	• Residual Energy (L+A) • Hop Count (A) • Packet Forwarding Indication* (L+A)	Reduced packet loss and latency is observed	Composite metrics are only tested against themselves, may select low-quality paths	JSIM - 100	Energy Consumption Rate, Packet Loss

L and A denotes if the metrics used in the work are utilized lexically or additively. * denotes a metric not specified in RFC 6551 – Continued on next page

Table 2 – continued from previous page

Name	Main Method	Metrics & Usage	Advantages	Shortcomings	Real / Simulator & # of Nodes	Evaluation Metrics
Energy Efficient Composite Metric for RPL [57]	• A lifetime and Latency Aggregateable Metric (L2AM) is introduced, which is a composite of ETX and Energy Efficiency metrics • Parent Selection	• Residual Energy (A) • Transmission Power* (A) • ETX (A)	Increased performance over baseline metrics	Increased reliability claim is not justified	Simulator not specified - 50	Network Lifetime, Residual Energy
SCAOF [58]	• Combines several weighted metrics for more reliable path selection • Parent Selection	• ETX (L) • Residual Energy (L)	Network churn is reduced and lifetime is increased	High risk of fragmentation is present, evaluated with low number of nodes	Real & COOJA - 10 & 20-30	Packet Loss Rate, Energy Consumption, Radio Duty Cycle
RPL Routing with Energy Efficient OF [59]	• A new, energy-based OF is proposed which handles parent selection according to residual energy • Parent Selection	• Hop Count (A) • ETX (L) • Residual Energy (L)	Significantly increased network lifetimes are claimed	Evaluated with low number of nodes	Real - 7	Network Lifetime, Delay, Topology Changes per Hour

L and A denotes if the metrics used in the work are utilized lexically or additively. * denotes a metric not specified in RFC 6551 – Continued on next page

Table 2 – continued from previous page

Name	Main Method	Metrics & Usage	Advantages	Shortcomings	Real / Simulator & # of Nodes	Evaluation Metrics
AL-ABAMO [60]	• A novel OF that utilizes the node traffic profiles • Parent Selection	• ETX (L+A)	Increased network lifetime	Increased energy consumption not handled	Real - 41	Network Lifetime, Network Delivery Ratio, Number of Parent Changes
CA-RPL [61]	• A congestion avoidance multipath routing protocol is proposed, based on composite metrics of custom-made delay root and ETX • Parent Selection	• Rank (A) • Delay (A) • ETX (A) • Packet Number* (A)	Improvements in congestion, throughput, packet loss and delay is observed	Evaluated with low number of nodes, increased energy consumption	COOJA - 20+	Throughput, Latency, Packet Loss Ratio
PC-RPL [62]	• A joint and adaptive control mechanism of the routing topology and node transmission is introduced • Parent Selection	• Hop Count (A) • ETX (A) • Signal Strength (L)*	Increased throughput and stability is observed and the hidden terminal problem is handled	May lead to increased energy consumption	Real - 49	Packet Reception Ratio, Number of Parent Changes, Packet Overhead

L and A denotes if the metrics used in the work are utilized lexically or additively. * denotes a metric not specified in RFC 6551 – Continued on next page

Table 2 – continued from previous page

Name	Main Method	Metrics & Usage	Advantages	Shortcomings	Real / Simulator & # of Nodes	Evaluation Metrics
Hybrid Routing with Thresholds [64]	• A hybrid approach using two metrics and threshold functions • Parent Selection	• Hop Count (A) • ETX (L)	Increased stability and reduced energy consumption	Evaluated with low number of nodes, unchanged PDR	COOJA - 20	Number of Parent Change, Packet Overhead, Energy Consumption
EL-RPL [65]	• Three weighted metrics are combined for parent selection • Parent Selection	• Load* (A) • ETX (L) • Residual Energy (L)	Increased reliability and network lifetime	Evaluated with low number of nodes	COOJA - 30	PDR, Delay, Hop Count / Network Size
Burst Traffic Scenarios [66]	• A traffic-aware metric that utilizes ETX and Parent Count is proposed • Parent Selection	• ETX (L) • Parent Count* (L)	Increased PDR and reduced power consumption is observed	Carries high risk of fragmentation, evaluated with low number of nodes	COOJA - 30	PDR, Energy Consumption

L and A denotes if the metrics used in the work are utilized lexically or additively. * denotes a metric not specified in RFC 6551 – Continued on next page

Table 2 – continued from previous page

Name	Main Method	Metrics & Usage	Advantages	Shortcomings	Real / Simulator & # of Nodes	Evaluation Metrics
Multiparent Routing in RPL [52]	• A new composite metric called ELT is introduced, used together with multipath forwarding • Multipath Routing	• ETX (L) • Residual Energy (L)	Energy consumption is reduced	Carries high risk of fragmentation	WSNet - 50	Network Lifetime, Delay, Number of Parent Changes, PDR
M-RPL [68]	• Provides temporary multipath routing if congestion occurs, which is detected by forwarding nodes • Multipath Routing	• PDR (L)	Increased throughput	High message overhead, Evaluated with low number of nodes	COOJA - 2-12	Throughput, Delay, Energy Consumption
Energy Equalization with Adaptive Multipath [69]	• Creates a novel energy dispersion (ED) metric and uses it in a multipath routing scheme • Multipath Routing	• Residual Energy (L)	Reduced delay, increased network lifetime	Prone to bottlenecks and to selection of low quality paths	Simulator not specified - 89	Network Lifetime, Delay, PDR, Residual Energy

6.3. Related Studies based on Custom Metrics

In this section, custom metrics developed by researchers to enhance RPL and improve load balancing are covered. Some of these metrics are directly employed in OF.

One of the earliest studies is based on neighborhood metrics [70]. The work aims to utilize information about neighbors that is available to facilitate improved routing decisions. The authors claim that routing through better node neighborhoods is more effective than routing through a better single path in terms of load balancing and stability. This claim is based on the observation that node-wise routing may be prone to decreased performance if the nodes in the path become unreachable, whilst routing through viable neighborhoods increases the chance of an uninterrupted routing.

The proposed approach consists of four phases: metric collection, parent selection, neighborhood metric calculation, and metric advertisement. In the first phase, a node gathers advertisement messages received from its neighbors and stores them in a neighborhood table.

These advertisement messages contain ETX and neighbor metrics that are calculated in the third phase of the algorithm. The neighborhood metric is given in Equation 11, where $e^{-\frac{\Delta\upsilon^2}{2\times\delta^2}}$ is a weight value applied to the neighbor, denoting its closeness to the parent node's neighborhood, while $\frac{1}{\iota^2}$ is a diminishing return in weight to each additional neighbor as a quadratic falloff, and Θ is the stability bound. In the parent selection phase, the node with the best overall combined metric score is chosen as the node's parent. In the third phase, the overall score of the neighborhood table is calculated by combining each score using a weighted function, where the weight is the distance of the neighboring node to the selected parent. In the final phase, the neighborhood metrics calculated in the previous phase are advertised through the network. Each node advertises its neighborhood metric to its neighbors. In order to ensure stability, a threshold mechanism is implemented, which compares the neighborhood metric scores, and then only allows parent switching if the higher score exceeds the threshold.

The results show that the use of neighborhood metrics provides reductions in the network load of up to 35% when compared to the baseline RPL based on ETX. However, the authors also claim that the method itself leads to higher overhead which requires higher processing power.

$$neighborhood\ Metric = e^{-\frac{\Delta\upsilon^2}{2\times\delta^2}} \times \frac{1}{\iota^2} \times \Theta \tag{11}$$

In [71], three separate improvements on RPL were introduced, namely Energy Load Balancing (ELB), Fast Local Repair (FLR), plus a combination of the two (ELB-FLR). ELB focuses on balancing energy usage and maximizing the nodes' lifetime, with a new objective function and mechanism for load balancing. For rank calculation, the objective function takes hop count and the energy level of the path into account, which is the summation of the residual energy of the nodes on that path. The load-balancing scheme works at the parent selection phase, with preferred parents alternating between the best possible parent and the second-best possible parent.

FLR, on the other hand, works by detecting nodes that have energy-bottlenecks and by balancing the traffic loads of these resource-constrained nodes. This approach aims to reduce the number of local repairs in RPL. The concept *siblings*, which are neighbors of a node with the same rank value, are then introduced. When repairing routes, these siblings are also taken into consideration in order to decrease both delay and energy usage.

In the merged ELB-FLR, the term *siblings* is redefined as routes having the same hop count. This, in practice, merges the two approaches by integrating objective function and ELB load balancing, with FLR's local repair mechanism and loop detection. The experimental results showed that all these proposals performed better in terms of overhead, delay, and packet delivery ratio when compared to the standard RPL. However, since the proposed mechanisms are based on changing parents, this might in turn decrease route stability.

In Stability Metric-Based RPL (sRPL) [49], a custom metric called stability index (SI) is introduced, which is based on the stability characteristics of a network, and is used for the selection of stable routes. The stability characteristics of a network are related to the number of control messages sent, with a lower number indicating the more stable network. A node in the network can calculate two types of SI values: node SI and DODAG SI. Node SI measures how stable a node is, whereas DODAG SI measures the overall stability of a DODAG topology. Using these two values, a node first chooses the most stable DODAG to join, and then selects the most stable nodes in that DODAG as its parents. In order to calculate SI values, a hearing window is implemented in a node, which records the number of control messages received from its neighbors in a promiscuous mode. A node calculates its own SI by counting the numbers of DIS, DIO, and DAO messages it transmitted in a set time period. The SI of a DODAG that the node belongs to can be calculated by the number of DIS, DIO, and DAO messages received by the node's neighbors.

The authors made several evaluations and compared the baseline RPL (using hop count and ETX) with SI-RPL, and also with the addition of ETX and then SI-ETX-RPL. The authors claimed that sRPL can reduce control message overhead by 90% and improve the packet delivery rate of the RPL by 20%.

In [50], on a new metric called *queue utilization* (QU) was introduced as the basis for Queue Utilization RPL (QU-RPL). The QU metric of a node is defined as the ratio of the number of packets in the queue to the total queue size. QU is used to estimate traffic congestion and selects parents accordingly. Unlike the standard RPL which uses ETX for parent selection, QU-RPL utilizes a weighted QU metric (see Equation 12), the hop count between the node and the LBR, and also the ETX metric. The equation for QU-RPL is given in Equation 13, where the weight of α ranges from 1 to 5 in the evaluations. A threshold for parent changing is also implemented in order to ensure stability. QU-RPL is shown to be useful in reducing losses in queues and increasing the ratio of successful packet delivery in comparison to the standard RPL. A possible drawback of QU-RPL is that it is only created for and tested within congested networks. Its performance and overhead in non-congested networks remains unclear, as the presence of the QU metric is only meaningful if congestion occurs in a node.

$$Q(k) = \frac{\text{Number of packets in queue}}{\text{Total queue size}} \tag{12}$$

$$R_Q U(p_k) = h(p_k) + 1 + ETX(k, p_k) + \alpha Q(p_k) \tag{13}$$

In [72], a method based on Radio Duty Cycle (RDC) was proposed for estimating energy consumption and to provide better load balancing in terms of energy. A new metric called Energy Estimation (EE) was introduced, with the node EE value calculated as the ratio of CPU time (the period when a node is awake) to radio time (the period when a node is transmitting). The authors claimed that this routing metric results in better energy distribution, higher reliability, and improved load balancing. However, the improvement claimed in terms of energy consumption was limited (1-2%).

Marco et al. [73] utilized information from the MAC layer with the aim of improving the accuracy estimation of network reliability. They proposed two new metrics: R-metric and Q-metric. The R-metric is defined as the end-to-end reliability between two nodes, and is envisioned as an extension of the ETX metric. However, it differs from ETX since it also takes into account the packet losses caused by MAC contention (collision of packets), and is calculated as the probability of a packet's correct transmission, kept within a preset number of retransmissions, in each link of the path. The Q-metric, on the other hand, distributes the forwarded traffic in the network in order to achieve load balancing. The main objective of the Q-metric is to increase the network lifetime. It is an optimization function, which computes the traffic between a given node and a candidate parent of the node.

Parent selection is handled by solving an optimization problem, which is minimizing power consumption whilst keeping within the reliability constraints. Load balancing is claimed to be guaranteed in the network by avoiding overloaded nodes with the help of the Q-metric. The proposed approach was compared with the standard RPL, based on ETX and Backpressure Routing [74]. While the experimental results showed that the proposed metrics improved end-to-end reliability (high PDR) and reduced power consumption, the experimentation was conducted using only limited numbers of nodes (7-18).

In [75], an extension to the RPL objective function was proposed in order to resolve load balancing caused by bottleneck nodes in the network. This extension, named LB-OF, attempts to distribute the child nodes of a bottlenecked node to other suitable parents in the vicinity (i.e., those sharing the same child nodes) so as to provide load balance and to increase the network lifetime. The new metric, called CNC (child node count), is used to select suitable childless nodes or nodes with a low number of children. Moreover, the calculation of the rank value of a node is suggested to be changed by adding consideration for the new CNC metric. Hence, in this case, while a node with a smaller rank has a high priority to accept new children, a node with a higher rank would not accept more children for parenting. While the study's results showed improvement compared to the standard OFs in terms of load balancing, it was seen to increase network power consumption. Additionally, the frequent parent changes caused by the proposed load-balancing scheme may create network instability.

In [76], an RPL improvement with a focus on load balancing was proposed for usage in smart grids. The improvement, named *OFQS* (Objective Function for Quality of Service), uses a multi-objective custom metric named *mOFQS* that combines residual energy (power state), delay, and link quality metrics. The *OFQS* itself is a derivation of MRHOF, retaining the rank calculation mechanism, but instead uses thresholds in order to increase route stability and to reduce frequent parent changes. The *mOFQS* metric can be seen in Equation 14, where α and β are two parameters that are always between 0 and 1, and whose combined sum does not exceed a value of 1, d is the delay metric, and *PS* is the power state metric. The authors stated that as a result of improving load balancing, passing through a longer and less reliable route was therefore possible with *mOFQS*. Their evaluations were conducted using three separate instances with different α and β values so as to simulate critical, non-critical, and periodic traffic. The evaluation results showed that *OFQS* increased the lifetime of the network along with PDR. However, stability was not taken into account in the work and the evaluations were conducted within a simulation with only a low number of nodes. However, it is worth mentioning that this work was later extended with new experiments using a higher number of nodes [77].

$$mOFQS = \frac{\alpha ETX * d}{PS^{\beta}} \tag{14}$$

In [78], Backpressure RPL (BRPL) was proposed, which allows users to smoothly combine any RPL Object Function (OF) with the backpressure routing [79]. Backpressure routing differs from standard routing mechanisms by omitting the source-to-destination path computation phase. This phase is replaced by making on-the-spot routing and forwarding decisions for each packet. For this computation, a backpressure weight is used, which is a function of link state information and local queue. In BRPL, a new link weight metric is calculated for neighbor nodes of a node running BPRL, which is a combination of queue length and rank, and accompanied by two novel algorithms, QuickTheta and QuickBeta. These algorithms provide support for varying traffic loads and mobility, respectively. QuickTheta adjusts the parameters of BRPL with respect to the congestion level of the network, without either prior assumptions or statistical models. The congestion level is calculated by observing the usage of the node's queue. The other algorithm, QuickBeta, observes the state changes of the neighbors (from online to offline, or vice versa) of a node within a given timeframe. The higher number of nodes changing their states means that they are more mobile. In summary, BRPL aims to increase the performance of RPL in terms of throughput, mobility, and adaptivity to network traffic. Notably, it is one of the few studies in the literature that considers the mobility of nodes in the network. The experimental results demonstrated that BRPL significantly improves network throughput, and is adaptable to changes in network topology and data traffic loads. However, while the proposed study showed an improvement in the presence of high traffic, it did not take network stability into account.

In [80], a new OF was proposed, named Smart Energy Efficient Objective Function (SEEOF), whose main aim is to balance the energy consumption among nodes and to increase the network lifetime. Two novel metrics constitute SEEOF: Estimated Remaining Life Time (ERLT) and linkETX. The ERLT metric, as its name suggests, aims to estimate a node's lifetime by calculating the rate that its energy is drained, based on the residual energy metric (see Equation 15). Meanwhile, the linkETX metric uses statistical message transmission and the acknowledgement data of a node in order to calculate ETX without probing the node itself.

The SEEOF itself combines these two metrics using Equation 16, where $\mathrm{MAX}_{\mathrm{LT}}$ is the maximum expected lifetime of a node, and the $\mathrm{ETX}_{\mathrm{Th}}$ and $\mathrm{ERLT}_{\mathrm{Th}}$ are the threshold values to increase stability. The results provided by the study's evaluations showed that the PDR was similar to MRHOF, while the network lifetime and energy balance was improved at the expense of stability. Moreover, the evaluations were conducted using a simulator with a low number of nodes (18).

$$ERLT = \frac{ResidualEnergy}{DrainRate} \tag{15}$$

$$SEEOF = \frac{linkETX}{ETX_{Th}} + \frac{MAX_{LT} - ERLT}{ERLT_{Th}} \tag{16}$$

In [81], the authors proposed a dynamic and distributed load-balancing scheme that was inspired by water flow behavior, called MLEq (Multi-gateway Load Balancing Scheme for Equilibrium). The MLEq scheme was proposed for networks with multiple DODAGs and applies load balancing so as to lower message traffic congestion. In implementing MLEq, a virtual level (VL) metric similar to the rank parameter of a DODAG, in the sense of its calculation, is used. With a high VL value indicating a high traffic level, the intersection of overloaded DODAGs should then be moved to areas with less traffic.

VL is transmitted using VIO (VL Information Object) messages, which are multicast to all neighbors. A node's VL is set by selecting the VIO with the shortest hop distance among the VIO messages it receives. This operation is repeated until all nodes in a DODAG have updated their VLs. The proposed scheme monitors the VL values of DODAGs, and shifts the topology such that that shared nodes between the DODAGs are changed to better accommodate load balancing. The main drawback of this work was seen to be increased energy consumption and new routing control messages, with modifications introduced to the standard RPL.

In [82], a braided [83] multipath extension to the standard RPL was proposed named as the Heuristic Load Distribution Algorithm (HeLD), which was aimed at improving load balancing and maximizing throughput. Two main contributions were specified in the study: a multipath routing mechanism, which forces nodes to use multiple parents at the same time, and balancing energy consumption between nodes that have the same hop count from the sink in a network, which is named as *tangential load balancing*.

The multipath mechanism constructs a DODAG by comparing hop count and route cost R(j), as shown in Equation 17. the route cost between node i to the sink going through the parent j is calculated using rank and cost of the link. Additionally, a weight value of parent j's share of node i's traffic rate is calculated using Equation 18, where the *P(i)* value is the parent set of node i. The tangential load balancing consists of three steps. First, the traffic rate of the parents is estimated by calculating the average number of received packets of each candidate parent within a given time, and second, the calculated traffic rates are compared.

As a third step, the traffic shares of the parents are changed gradually in order to equalize and provide balance in the network load. The experimental results showed that HeLD provided a 23% increase in network lifetime and a 28% increase in throughput, when compared to the standard RPL. However, it was pointed out that HeLD may not provide the same results for a heterogeneous topology, which is very common in real-life situations.

$$C_{ij} = R(j) + c_{ij} \tag{17}$$

$$w_j(i) = 1 - \frac{C_{ij}}{\sum_{j \in P(i)} C_{ij}} \tag{18}$$

In [84], an extension to RPL, called IPRL (Improved RPL), was proposed. The IRPL extension utilizes the lifecycle index (LCI) as the objective function for path selection. The LCI metric represents the overall completion cost of a packet transmission of a sender node as a function of its data throughput, the average number of forwards, the ratio of time used for the transmission, and the energy delivery rate, which is time multiplied by the energy consumption of the node. A multipath scheme is implemented to ensure that bottlenecks are avoided and load balancing is thereby maintained. The scheme showed better performance in terms of network load, end-to-end delay, packet delivery ratio, optimal parent node change frequency, energy consumption, and network lifetime.

A tabulated version of the works covered in this subsection is presented in Table 3. Compared to the previous subsection, the works reviewed here exhibit more novel methods in their aim to improve load balancing in RPL. Moreover, some of the works are extensions or enhancements of previous works. It can also be said that the improvements reported in the works covered in this subsection are more significant than those previously introduced. In terms of the approach, testing, and results, [49] and [84] are seen to stand out, while [73] is considered novel in the way that it utilizes the MAC layer.

Similar to the studies based on standard metrics, the proposed approaches were mostly tested on networks with only a low number of nodes, whilst some could be said to be very much application-specific, such as for smart grids or home automation [76], or suited only to limited types of topology (homogeneous) or traffic patterns (i.e., no variance in traffic). Additionally, except for [78], mobility was not the primary focus of the works covered in this subsection.

Table 3: General information about the evaluated works that are based on custom metrics

Name	**Main Method**	**Metrics & Usage**	**Advantages**	**Shortcomings**	**Real / Simulator & # of Nodes**	**Evaluation Metrics**
Neighborhood Metrics [70]	• Introduces neighborhood metrics • Parent Selection	• ETX (L+A) • Neighborhood Metric* (A)	Enhances parent selection	Reduced performance in networks with higher number of nodes, Requires high processing power, lacks reliability metrics	Real - 49 & 298	Load Distribution, Number of Sent Packets
RPL-based Multipath Routing [71]	• An expected lifetime metric is proposed • Parent Selection	• Residual Energy (L+A) • Hop Count (A)	Removes energy bottlenecks	Disregards and decreases stability	OMNET++ - 12	Message Overhead, Delay, Residual Energy
Stability Metric Based RPL [49]	• Uses a new metric named stability index • Parent Selection	• Number of Control Messages* (L+A)	Improves PDR, Reduces overhead	Not tested in real testbeds	ns-2 - 1024	Message Overhead, PDR, Latency

L and A denotes if the metrics used in the work are utilized lexically or additively. * denotes a metric not specified in RFC 6551 – Continued on next page

Table 3 – continued from previous page

Name	Main Method	Metrics & Usage	Advantages	Shortcomings	Real / Simulator & # of Nodes	Evaluation Metrics
QU-RPL [50]	• Queue utilization metric enhances preferred parent selection • Parent Selection	• Hop Count (A) • ETX (L)	Reduces packet losses and improves PDR	Performance in uncongested networks is unclear	Real - 30	Average Parent Changes, PDR
RDC [72]	• An estimated energy consumption metric is introduced • Parent Selection	• Energy Estimation* (L)	Improves energy distribution and reliability	Limited improvement in energy consumption	COOJA - 25	PDR, Residual Energy
MAC-Aware Routing Metrics [73]	• Two new metrics are introduced; where R-Metric represents reliability and Q-metric represents optimal traffic • Parent Selection	• R-Metric* (A) • Q-Metric* (A)	Increased reliability and decreased energy consumption	No testbed evaluation, evaluated with low number of nodes	TOSSIM - 7-18	Number of Parent Changes, Energy Consumption, PDR

L and A denotes if the metrics used in the work are utilized lexically or additively. * denotes a metric not specified in RFC 6551 – Continued on next page

Table 3 – continued from previous page

Name	Main Method	Metrics & Usage	Advantages	Shortcomings	Real / Simulator & # of Nodes	Evaluation Metrics
LB-OF [75]	• Solves bottlenecks by distributing child nodes in the network • Parent Selection	• Child Node Count* (L)	Increased lifetime of the network	Lack of comparison to other methods	COOJA - 17-50	PDR, Energy Consumption
OFQS [76][77]	• Creates a custom QoS metric aimed at minimizing energy consumption while balancing the load • Parent Selection	• ETX (L) • Delay (L) • Residual Energy (L)	Increased lifetime of the network and PDR	Reduced stability	COOJA - 35 [76] - 67 [77]	Residual Energy, Delay
BRPL [78]	• Allows the combination of backpressure routing with any RPL OF • Parent Selection	• Link Weight* (A)	Increased throughput and adaptability	Lack of reliability metrics in the implementation	Real & COOJA - 100 & 100	Packet Loss Ratio, Delay

L and A denotes if the metrics used in the work are utilized lexically or additively. * denotes a metric not specified in RFC 6551 – Continued on next page

Table 3 – continued from previous page

Name	Main Method	Metrics & Usage	Advantages	Shortcomings	Real / Simulator & # of Nodes	Evaluation Metrics
SEEOF [80]	• Uses novel metrics to estimate energy drain • Parent Selection	• ETX (L) • Residual Energy (L)	Increased lifetime of the network and load balancing	Reduced stability, Evaluated with low number of nodes	COOJA - 18	Network Lifetime, Energy Consumption
MLEq [81]	• A decentralized load balancing scheme, based on water flow, is proposed to lower message traffic congestion • Multipath Routing	• Virtual Level* (L+A)	Increased network capacity and overhead	Increased energy consumption	ns-2 - 100	PDR, Load Homogeneity
Heuristic Load Distribution Algorithm [82]	• Utilizes multipath DODAGs • Multipath Routing	• Hop Count (A) • Route Cost* (A)	Increased throughput	No real testbed experiments	Simulator not specified - 50-100	Network Lifetime, Throughput

L and A denotes if the metrics used in the work are utilized lexically or additively. * denotes a metric not specified in RFC 6551 – Continued on next page

Table 3 – continued from previous page

Name	Main Method	Metrics & Usage	Advantages	Shortcomings	Real / Simulator & # of Nodes	Evaluation Metrics
Energy Balancing RPL Protocol [84]	• An objective function named Life Cycle Index is introduced to improve path selection • Multipath Routing	• Life Cycle Index* (L)	Increased performance in PDR, reduced delay, parent change, energy consumption	Lack of comparison to other methods	Real - 100	PDR, Delay, Residual Energy, Number of Parent Changes

6.4. Related Studies Utilizing Heuristic Approaches

The remainder of the works reviewed in this survey are grouped within this subsection. In these works, several different techniques have been employed aimed at improving load balancing in RPL. While some focused on changing the timing of messages, others came up with novel methods such as probabilistic approaches, changing the topology, utilizing multipath routing, and artificial intelligence (AI)-based approaches.

In [85], the New-Trickle algorithm, an improvement over RPL's standard Trickle algorithm was introduced specifically to address the short-listen problem, which occurs due to non-synchronized Trickle intervals between neighbors in a DODAG. These intervals drastically impact upon the Trickle's suppression mechanism, which in turn reduces scalability. The New-Trickle algorithm optimizes the Trickle algorithm by modifying the second step of the original Trickle algorithm, which resets the timer and chooses a random value for the countdown. As asynchronous intervals are the cause of the short-listen problem, reducing them helps to decrease the propagation time of Trickle with no significant cost. Moreover, the new-Trickle algorithm is claimed to provide faster updates, yielding a propagation time more than 10 times faster than Trickle. The authors claimed that New Trickle is also an improvement over RPL's Trickle algorithm in terms of load balancing. The small listening periods of the original Trickle algorithm were considered prone to load imbalance, whilst the New-Trickle algorithm affords competing nodes an equal or similar chance to transmit their updates, which thereby helps to alleviate bottlenecks in the network.

In [86], the authors proposed a scheme named ORPL-LB (Load-Balanced Data Collection through Opportunistic Routing). Opportunistic routing (OR) is a method similar to multipath routing schemes, but which differs from traditional methods in its selection of the next hop. In traditional routing, the route is determined prior to a packet being transmitted, whereas in OR, the next hop is selected during transmission based on the availability of the next node in the route. In this way, traffic and congestion can largely be avoided. The ORPL-LB scheme improves upon OR with an additional concern for load balancing, which is made possible by implementing a sleep/wake-up cycle for the nodes. The nodes experiencing high traffic or low energy tend to sleep more, and when a packet tries to determine its next hop, the sleeping nodes are excluded from the potential next hops. From the simulation results, it could be seen that ORPL-LB significantly reduces (by approximately 40%) the worst node's duty cycle, with little or no impact on either the packet delivery ratio or latency.

In [87], a dynamic parent selection scheme for RPL was proposed. The scheme, named Energy-Aware and Load Balanced Parent Selection, focuses on load balancing improvement and energy consumption. The authors aimed to distribute traffic in an even manner using a modified cluster-tree MAC, which is the topology of the IEEE 802.15.4 [19] standard. The cluster-tree MAC approach is both compatible with RPL and also permits the selection of multiple parents. For each packet, the preferred parent is selected based on a composite metric incorporating residual energy and recent load on paths to the sink. While the work also utilizes routing metrics, its cluster-tree MAC distribution scheme is novel, and thus can be considered apart from the metric-based works. As can be observed from the experimental results, the mechanism extends network lifetime and improves network performance in terms of end-to end delay and packet delivery ratio.

In [88], a scheme-titled Minimum Degree RPL (MD-RPL) was introduced. As its name suggests, minimum-degree spanning trees [89] are utilized in order to provide load balancing for RPL. Minimum-degree spanning trees algorithm aims to reduce the degree (height) of a tree. In this way, the network would be wider instead of taller, and there should be fewer cases of congestion. The algorithm is divided into four phases. First, the maximum degree of the tree is determined; whilst in the second phase, the node with the highest degree searches for an alternative edge with a lower degree to connect to. The third phase is optional and is utilized if more than one alternative edge is found. This phase maintains the efficiency of the algorithm by limiting the connection changes, similar to the parent-changing thresholds seen in some other works. The final phase handles the actual swap of the nodes so as to reduce the degree. The experimental results showed up to 15.6% reduction in energy consumption, which implies an improvement in the lifetime of the network.

The following works are characterized by their utilization of predictive methods to improve load balancing in RPL.

In [90], the authors proposed a hybrid extension to [55], in which multiple mobile sinks are deployed and moved to nodes with high residual energy so as to prevent node depletion. The method combines the metric-based approach of [55] with a predictive model that attempts to calculate the future destination of the mobile sink. The main motivation behind this approach is the unpredictable nature of mobile sinks, which can easily change their position or go online or offline. The predictive model developed by the authors was named as on-demand sink discovery. Rather than propagating the discovery messages through the whole network topology, nodes try to discover a sink within its vicinity. How far the discovery will go is determined by the ω value. In the case of multiple sink discoveries, the sink with the shortest distance is selected. While the work claimed improvements in load balancing and a decrease in retransmissions, no results were presented by the authors of any meaningful comparison. Moreover, the predictive method itself was not specified in detail.

In [39], the authors proposed LB-RPL (Load Balanced Routing for RPL), which aims to mitigate the load imbalance problem in a decentralized, non-intrusive, and reliable way. In order to achieve this, the authors devised an analytical model which quantifies the effect of limited resources and the general reliability of the LLNs. The analytical model suggests that packet sources (number of nodes that send packets) are critical to the general packet delivery rate. Additionally, the packet drop probability is another important metric that should be considered. Based on this model, a two-pronged approach for LB-RPL was proposed. The first goal is to detect workload imbalance, whilst the second is to achieve load-balanced data forwarding. For the first goal, a buffer utilization counter is used to count the average number of packets in a node's buffer over a certain period. Using this counter, the transmission of the DIO messages can be put on hold, which would result in improved load balancing in congested nodes. The second goal requires the calculation of the probability of a node to forward a data packet to a particular parent node. The calculation itself is presented as shown in Equation 19, where i and j denote the node and its parent, while k is the number of potential parent nodes. The f_{ij} value is used to find whether or not a possible parent is congested. A parent with a higher probability to forward a packet is considered as being the more suitable. The simulation results showed that LB-RPL is successful at spreading out the workload among the nodes in the network. Additionally, it results in a decrease in both packet loss and delay.

$$f_{ij} = \frac{(1 - p_{ij}^{c})}{\sum_{j=1}^{k}(1 - p_{ij}^{c})} \tag{19}$$

There are only a few AI-based approaches in the literature that target the load-balancing problem. In [91], the authors proposed a scheme named LBO-QL (Load Balanced Optimization based on Q Learning). LBO-QL utilizes Q-Learning in order to achieve the goal of preserving child node number in a network, which would result in a more balanced network. In Q-Learning, the node only needs to know the immediate candidate parent nodes, which can greatly reduce traffic overhead. A reward table was created to integrate Q-Learning with RPL DODAG construction, which maintains the relations between neighbors. According to the study's experimental results, convergence time and PDR showed improvements compared to the baseline RPL. The energy consumption levels were shown to be similar, and a reduction in control messages was observed. LBO-QL is the only work that utilizes machine learning to improve load balancing in RPL, hence it is presented within this subsection. The shortcoming of this work, however, was the use of only a low number of nodes in the evaluations. Moreover, the always-on nature of Q-Learning, and its reliance on a network hub for its calculations, somewhat limits its scalability.

In [92], a new energy-aware routing protocol named *FLEA-RPL* (Fuzzy Logic-based Energy-Aware RPL) is proposed. *FLEA-RPL* uses fuzzy logic techniques to create a load-balanced network with better distributed load and residual energy among the nodes. While fuzzy logic is a popular concept in RPL improvements [93][94][95], a fuzzy logic-based work that focuses on load balancing is considered to be novel. Three routing metrics are selected in the implementation of *FLEA-RPL*: Load, Residual Energy, and ETX. In the fuzzification process, three linguistic variables are set for these metrics. For example, the load metric has light, normal, and heavy load values as its linguistic variables.

A rule base consisting of 27 rules (with different metric states) was implemented to create the output named "Quality," which has a value between 0 and 100. After the fuzzification and the defuzzification stage, the quality variable is obtained for the parent selection process. Based on the results, it can be said that FLEA-RPL improved the network lifetime and packet delivery ratio. Moreover, it exhibited a better distribution of residual energy, which would indicate better overall load balancing. In the future, the authors aimed to address lowered route stability and lack of mobility support.

The studies covered in this section are outlined in Table 4. The studies propose different techniques ranging from using cluster-tree based topologies [87] to predictive [90] and machine learning methods [91] in order to provide load balancing. The advantages that are documented in these studies are generally increased throughput and PDR along with improved load balancing. Similar to metric-based studies, most works are tested on network simulations with a low number of nodes and most exhibit high overhead in their methods.

Table 4: General information about the evaluated works that are based on heuristic methods

Name	**Main Method**	**Metrics & Usage**	**Advantages**	**Shortcomings**	**Real / Simulator & # of Nodes**	**Evaluation Metrics**
New-Trickle Algorithm [85]	• An optimization of the trickle algorithm is proposed	-	Faster propagation times without the accompanying overhead is observed	May not work as effectively in all scenarios	Simulator not specified - 400	PDR
ORPL-LB [86]	• Proposes a scheme named opportunistic routing, which decides where to go on-the-fly	-	Worst node duty cycle is reduced significantly without impacting PDR or latency	Lack of comparison to other methods	Real - 93	Wake-up Interval, Radio Duty Cycle
Load Balanced Parent Selection in RPL [87]	• A cluster-tree MAC is utilized with composite metrics • Parent Selection	• Residual Energy (L) • Load* (L)	Improved network lifetime and PDR	High message overhead	WSNet - 144	Network Lifetime, Delay, PDR

L and A denotes if the metrics used in the work are utilized lexically or additively. * denotes a metric not specified in RFC 6551 – Continued on next page

Table 4 – continued from previous page

Name	Main Method	Metrics & Usage	Advantages	Shortcomings	Real / Simulator & # of Nodes	Evaluation Metrics
MD-RPL [88]	• Overloaded nodes are identified and readjusted using minimum-degree spanning tree	-	Reduced power consumption	High message overhead, evaluated with low number of nodes	COOJA - 20-45	Energy Consumption
A Hybrid Routing Protocol for WSNs [90]	• Utilizes multiple sinks which are deployed predictively to high energy nodes	• Residual Energy (L)	Prevents node depletion	No evaluation present and no results are produced	Simulator not specified - Not specified	Not specified
LB-RPL [39]	• DIO messages are timed to the workload of the network	-	Better network workload spread	Lack of reliability metrics in the implementation	ns-2 - 1000	Delay, PDR
LBO-QL [91]	• Q-Learning is utilized to preserve the number of child nodes in a network	-	Increased stability	Evaluated with low number of nodes, no real testbed experiments	COOJA - 14	Energy Consumption, PDR

L and A denotes if the metrics used in the work are utilized lexically or additively. * denotes a metric not specified in RFC 6551 – Continued on next page

Table 4 – continued from previous page

Name	Main Method	Metrics & Usage	Advantages	Shortcomings	Real / Simulator & # of Nodes	Evaluation Metrics
FLEA-RPL [92]	• Utilizes fuzzy logic to create a quality score using routing metrics • Parent Selection	• Load* (L) • Residual Energy (L) • ETX (L)	Better network lifetime and PDR	Lowered stability, no real testbed experiments	COOJA - 100	Residual Energy, Number of Parent Changes, Delay

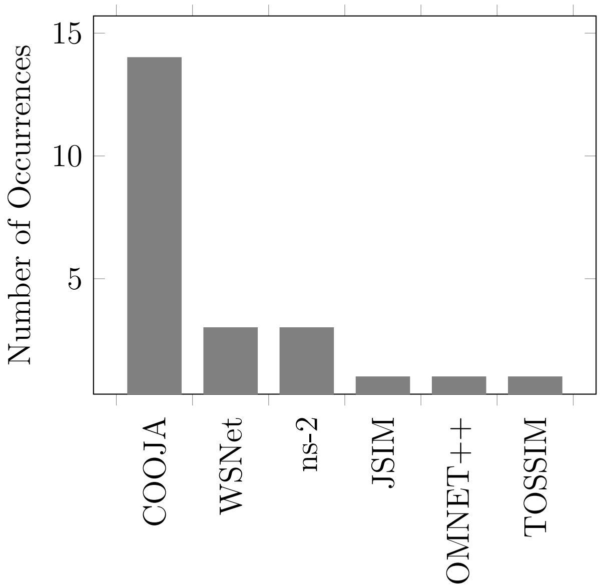

Figure 6: Distribution of simulators used in the reviewed works

6.5. General Discussion of Related Studies

To summarize, the studies in the literature failed to fully overcome the load-balancing problem and limitations of RPL. The concept of load balancing itself, and its context within the reviewed works, is also ambiguous in some instances. For example, while some works specify that a general similarity among the remaining energy levels of a network's nodes indicates a balanced load (network lifetime is another evaluation metric that is generally interpreted as an indicator of a balanced load), other works do not specify what constitutes a balanced load. Moreover, most of the improvements are only limited in scope and scale, disregard RPL's other limitations, and have not been thoroughly evaluated. The most common shortcomings are explained in more detail as follows.

Limited Evaluations: Not many of the mentioned works were evaluated within a real environment, with network simulators having been used instead. The distribution of simulators used in the reviewed studies is illustrated as shown in Figure 6. As can be seen, COOJA stands out as the most popular among the simulators. The main reason for its popularity is that ContikiOS, in which COOJA operates, is an open-source operating system focused on IoT devices in general. Whilst this makes COOJA both accessible and easy to use, there are also certain performance constraints, such as low performance or crashes when simulating an environment with a high number of nodes.

While it is useful for proof-of-concept studies, evaluations based on simulations might not fully reflect all aspects of real scenarios. Almost 30% of the works reviewed evaluated their approaches on real testbeds, and the number of nodes used in these testbeds was less than 50, as in home automation systems. Even evaluations using simulators have been conducted with a low node numbers. Additionally, a standard testbed for evaluation is needed in order to more accurately compare each study's performance.

While the RPL standard intends to run on LLNs that consist of between a few dozen to thousands of sensor nodes [33] in real-life situations, some of the works [58][59][65][96] used small networks (consisting of less than 50 nodes). The low number of nodes in the evaluated networks cannot be considered adequate, since it is suggested that at least 25 nodes are used in order to see the multihop characteristics of RPL [8]. Furthermore, the scalability of the proposed approaches are mostly not even discussed.

Lack of Reliability: While some [64][70][76] of the works propose load-balancing enhancements by distributing the energy load among the nodes, they do not elaborate about their results, not in the context of network reliability, which is an important criterion for performance. It can be said, therefore, that most of the reviewed works were only concerned with energy, and its subsequent effects on routing. Metrics such as PDR and throughput can be used to measure a network's reliability, and also to make routing decisions. Lack of reliability may cause fast depletion of energy and high overhead. Lack of reliability is also closely linked with stability. Utilizing multi-objective optimization techniques to find a trade-off between reliability and a balanced network could be a future research direction worthy of exploration.

Lack of Standardization in Performance Metrics: Among the reviewed works, the determination of a load-balanced network was not standardized. The works employed several performance metrics in order to evaluate their proposed methods or schemes, and a standard set of evaluation metrics would be needed so as to efficiently and effectively evaluate and compare the works. Most of the works used network lifetime, remaining energy, and PDR to evaluate their methods, while the more sophisticated and accurate metrics such as load distribution and load homogeneity were not commonly applied.

High Risk of Fragmentation: Some [52][56][58][61][66] of the proposed works used several metrics in their implementations, and/or they attempted to collect large amounts of data from the nodes, which led to DIO messages containing large volumes of information with correspondingly large sizes. As these messages would inevitably be subdivided into smaller parts and then transmitted independently, the loss of a packet would lead to retransmissions which would further increase the traffic, and thereby lead to reduced overall performance.

Selection of Low-Quality Paths: As mentioned in the previous sections, a path's cost of routing is computed by combining the costs of its constituent links in some manner through the combination and utilization of varying metrics. If these metrics are not thoroughly considered (such as using only hop count or delay), a path that may seem a better choice may in fact present a lesser performance (in terms of energy consumption or delay) when compared to a path with a higher number of hops. Moreover, some of the works [50][56][85] that only considered the immediate nodes when determining routes tended to lack awareness about the network as a whole. For example, in [50], this led to decreased performance in uncongested networks, because the method only aimed for congestion avoidance within its vicinity.

Lack of Utilization of Multiple Instances: While multiple instances are defined as one of the RPL's key features, none of the works used them to improve RPL through cost reduction, energy consumption, or complexity. Utilizing multiple instances also has the advantage of using multiple metrics with different objectives, which could be suited to different types of routing for different purposes, such as for routing different message types or those with different priorities. In this way, there would be less of a need to create an all-rounder routing scheme which would be more computationally complex or require higher resources.

Difficulty of Understanding the Complex Environment: All of the metric-based studies evaluated in this study employed manmade metrics. However, LLNs are complex environments due to their special characteristics, such as having low-power nodes and lossy links. Moreover, different trade-offs should be considered whilst designing a routing protocol for this complex environment such as reliability and/or stability. Humans are not particularly adept at selecting good choices when complex trade-offs have to be considered. It could be even harder to perceive the environment when mobility is present. Artificial intelligence-based techniques could be better suited to such complex and/or dynamic problems. However, only a few approaches [91][92] investigated the use of AI-based techniques for the improvement of load balancing. Moreover, only one study [55] took mobility into account. Therefore, much greater research is needed in this area; for example, researchers could investigate the automated generation of new metrics, or defining dynamic thresholds that need to be adapted according to mobility or traffic patterns, etc.

7. Conclusion

In this survey, the problem of load balancing in RPL was identified, with works subsequently evaluated that aimed to improve RPL. The examined works were categorized under three groups: first, papers that used metrics defined in the RPL standard; second, the use of custom-defined metrics; and third, heuristic methods not based on metrics such as machine learning techniques.

The evaluation provided insights about how each of these works aimed to improve load balancing in RPL, and the trade-offs involved in achieving such improvements. It was observed that most of the works focused on energy-consumption metrics. As the energy constraints of IoT devices are known to be very stringent, the focus appears to have been predominantly on energy consumption. It should be noted, however, that improving energy consumption may also result in increased latency or low PDR.

One of the dangers of collecting additional information to propose more advanced load-balancing techniques is the risk of fragmentation due to large message sizes. Fragmentation results in an increased number of packets, which thereby diminishes gains made in load balancing and which could also be possible through the use of more information.

Most of the works performed experiments via simulations, and usually on a small number of nodes. Although that approach may be sufficient for a home IoT scenario, LLNs are considered to mostly consist of thousands of nodes; hence, the scalability of RPL should be investigated more thoroughly. Lastly, metrics require standardization in order to be able to accurately evaluate a load-balanced network, and also to make effective comparisons.

In addition to these issues, mobility and multiple instances of RPL were overlooked in most of the studies evaluated in this survey. Although most IoT networks were found to be static, it is indeed possible that there are also IoT networks with limited mobility. Besides, multiple instances are supported in the RPL standard, but there has been almost no work found that considers routing in the case of multiple instances.

The evaluation also led to the conclusion that there has been no perfect solution found to improve load balancing in RPL, yet. Further customization and tweaking of routing metrics and objective functions would likely only lead to small gains, which are then associated with other drawbacks. Thus, there is a need for novel techniques to further the effort in this area. Techniques such as the utilization of multiple instances, using AI-based approaches for automatic metric generation, and threshold determination have yet to be fully explored, but certainly show considerable promise.

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