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A Comprehensive Survey on Objective Functions in RPL Routing with Various Networking and Application Scenarios

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Abstract

Technological breakthroughs in the Internet of Things (IoT) have positioned the Routing Protocol for Low-Power and Lossy Networks (RPL) as a cornerstone for enabling connectivity in resource-constrained and highly dynamic environments. The Objective Function (OF) lies at the heart of RPL, which guides parent selection and route optimization. However, conventional OFs are mostly limited to basic metrics, frequently overlook critical factors such as link heterogeneity, dynamic traffic patterns, energy fairness, reliability, and application-specific Quality of Service (QoS) demands. This survey presents a systematic and technically rigorous review of 108 influential studies published between 2015 and 2024, aimed at focusing on the multidimensional challenges of OF design across varied network environments and application scenarios. Rather than offering a broader overview like existing surveys, it critically assesses the adaptability of different OFs, the trade-offs they introduce, and evaluates their impact on routing performance, while identifying unresolved research gaps that limit scalability, interoperability, and practical deployment. It further highlights emerging solutions such as multi-metric optimization, context-aware routing, and machine learning–based OFs as more promising strategies to enhance the resilience and efficiency of RPL. By integrating fragmented knowledge into a cohesive framework, this survey not only strengthens theoretical understanding but also outlines a research agenda for developing next-generation OFs that are adaptive, cross-domain, and ready for practical implementation, thereby creating lasting impact for future IoT deployments.

Keywords: Industrial Internet of Things (IIoT), Objective function (OF), RPL, Quality of Service (QoS), Smart Applications.

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1. Introduction

The emergence of the IoT smart environment marks a significant breakthrough in modern society, with the goal of seamlessly connecting all ”smart things” to the Internet [1] [2]. IoT has significantly advanced the development of numerous applications across various sectors, including smart buildings, smart grids, smart cities, smart homes, and smart healthcare, enhancing people’s daily lives and routines.

A routing Protocol for Low-Power and Lossy Networks (RPL) was developed by the Internet Engineering Task Force

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(IETF) community, specifically for Low-Power and Lossy Networks (LLNs) in an IoT environment [3]. The significant properties of RPL are reliable, energy-efficient, scalable, and flexible routing solutions that satisfy the specific requirements of an IoT environment. RPL enables a wide range of IoT applications to operate seamlessly by effectively addressing the unique challenges of LLNs. The OF plays a significant role in RPL as it tailors routing decisions according to the unique requirements and constraints of different IoT applications [4].

The RPL-OF enhances network performance in terms of reliability, energy efficiency, latency, load balancing, mobility, scalability, and Quality of Service (QoS) by optimizing routes based on selected metrics. This customization and flexibility are crucial to meet the diverse requirements of IoT and to ensure efficient, robust, sustainable, and victorious network operations. To date, only the hop count and a widely used link reliability metric known as ETX are considered in the standardized OFs. While ETX-based RPL-OF is reliable for choosing high-quality links and shrinks transmission counts, it is limited to integrating inadequate considerations that are energy efficiency, load balancing, dynamic network conditions, latency, mobility, scalability, link capacity, QoS, and security, which are very crucial for highly adapting the OFs to distinct IoT applications [5] [6].

Later, advanced or hybrid OFs are introduced to overcome the drawbacks of fundamental OF and optimize RPL routing for the demanding requirements of diverse IoT applications. In this survey, a comprehensive analysis and exploration of various types of OFs and their suitability and implementations in IoT applications are explored.

IoT is expected to grow significantly in the upcoming years, with Cisco estimating approximately 100 billion connected devices by 2025. This immense growth of RPL has attracted much interest from the academic and industry community because of its capacity to create dependable and effective routes between nodes in LLNs, meet diverse performance requirements like energy efficiency, load balancing, dynamic network conditions, latency, mobility, scalability, link capacity, QoS, and security [7]. OF is the heart of RPL that defines objective-based parent selection in the root node during routing [8].

Even though different OFs have been introduced in recent years, the IETF working group has still identified only two as the primary OFs for RPL. The Minimum Rank with Hysteresis OF (MRHOF) and OF Zero (OF0) [9,10]. A detailed analysis of OF adaptability in different IoT application scenarios is vital to certify that the selected OF can exactly meet the specific requirements and constraints of each IoT application.

Thus, it is essential to consider diverse performance metrics, dynamic network conditions like mobility and varying link characteristics, scalability, energy constraints, load-balancing characteristics, reliability, adaptation complexity, and security. Moreover, a thorough analysis of wider OFs assists in selecting the most appropriate OF for ensuring seamless performance, efficiency, and reliability for distinct IoT applications.

1.1. Motivational Factors and Contributions

The primary motivation of this survey is to explore a comprehensive analysis of various RPL-OF adaptability across a wider range of IoT applications. The core factor of this survey is to clearly understand how disparate OFs impact the critical aspects of IoT network operation. Certain RPL-OFs offer priority to energy efficiency, which leads to prolonged network lifetime and shrinks power consumption.

Some other RPL-OFs are latency-based, and they focus on reducing end-to-end delay, which is highly fit for real-time IoT applications in smart industries and intelligent healthcare. Table 1 highlights the potential contributions of the survey compared to the existing surveys.

Plenty of RPL-OFs are introduced in the literature, and they lack the ability to comprehensively analyze the performance of such OFs under different applications [3] [7] [11] [12]. Thus, the primary motivation is to perform an in-depth analysis of diverse RPL-OFs with the aim of optimizing performance across various IoT applications to resolve challenging conditions and constraints. A better understanding of how different OFs perform in terms of energy efficiency, scalability, reliability, mobility, load-balancing, security, QoS, and adaptability can assist in developing tailored routing strategies that enhance the efficiency, reliability, and robustness of distinct IoT applications. This analysis precisely addresses the benefits and limitations of RPL-OFs using various parameters, thereby guiding future innovations in the routing of smart IoT environments.

Table 1. Comparative Analysis of Proposed Survey with Existing Surveys

Author	Types of Review	Main Factors Discussed in the Paper										
		RPL	Std OF	New-OF	Single metric	Composite Metric	OF Customization	OF Adaptability on Diverse	OF Analysis on Diverse Network	Key Findings Related to	Considerations related to	RPL-OF related Future Directions
Ghaleb, B et al.,(2019) [11]	General RPL Survey	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗
Kim, H.-S et al., (2017) [12]	General RPL Survey	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗
Kharrufa, H et al., (2019) [3]	General RPL Review	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗
Darabkh, K et al.,(2022) [7]	Comprehensive RPL survey	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗
Proposed survey	Systematic RPL-OF Survey	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

- Holistic RPL-OF Coverage: Unlike conventional surveys [3] and [7], which primarily provided broad overviews of RPL and its OFs, this work systematically analyzes both standard and emerging OFs in depth across different network settings and heterogeneous applications. It examines the impact of single and composite metrics, highlights the significance of customization, and demonstrates their influence on routing performance in resource-constrained IoT environments.

- Contextual and Application-Aware Analysis: Existing surveys [11], [12] offered only limited insights into the adaptability of OFs across diverse applications and network scenarios. The proposed survey addresses this gap by framing a structured analysis that links OF strategies to heterogeneous IoT requirements, revealing trade-offs in scalability, energy efficiency, and reliability across diverse deployment scenarios.

- Forward-Looking Research Directions: Earlier reviews [3], [7], [11], [12] often neglected multifaceted considerations of design and provided structured guidance for future RPL-OF research. In contrast, this work introduces a unified taxonomy that integrates fragmented advancements and presents forward-looking directions such as AI-driven optimization, cross-layer metric fusion, and security-aware OF design to enable resilient and adaptive IoT routing.

1.2. Methodology of Literature Review

This survey formulates the following Research Questions (QRs) to perform in-depth analysis and comparison of RPL-OFs across various IoT application scenarios.

- RQ1: How does the RPL routing protocol employ various OF designs to optimize the RPL routing performance in LLN?
- RQ 2: What are the essential RPL OFs to customize various network scenarios?
- RQ 3: How adaptable are various OFs to emerging IoT application scenarios for seamless performance?
- RQ 4: What are the potential future opportunities that exist for developing more effective OFs?

1.2.1. Steps for Conducting the Survey

This Systematic Literature Review (SLR) follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) reporting guidelines, which significantly improve the quality, transparency, and reproducibility of the survey. The methods utilized in the SLR are planning, executing, and reporting. The planning phase involves outlining the objectives, search strategy, inclusion and exclusion criteria, and methods for selecting relevant studies. The execution phase searches the materials from selected sources and selects the most relevant studies using automated and manual screening methods based on inclusion and exclusion criteria. The reporting phase presents the selected most relevant studies using publishing year, author, publisher, country, gender, index, and the number of citations. The SLR provides a clear and replicable step-by-step method to tackle the formulated research questions. Figure 1 illustrates the steps in an SLR on OF in RPL with an IoT application scenario.

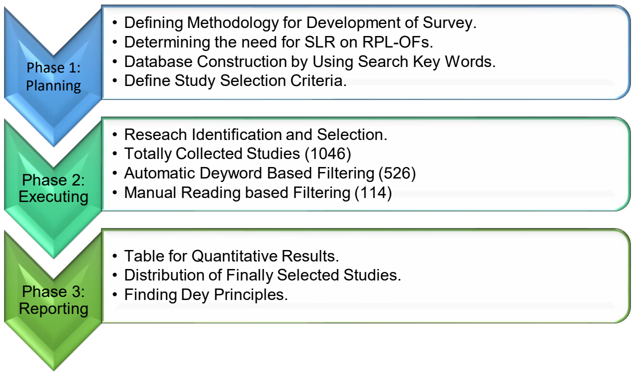

Figure 1. SLR steps for OF-RPL Analysis

Search Process: An extensive search was conducted for research papers across prominent academic platforms, including IEEE Xplore, Springer, Science Direct, ACM Digital Library, Wiley Online Library, Taylor and Francis, Hindawi, and MDPI. Keyword strings that were employed, such as 'RPL Survey', 'Survey on OF in RPL', 'Survey on OF in Smart application', 'RPL in IoT application', and 'OF in IoT', were utilized to narrow down the search criteria. The search is conducted across prominent digital libraries, high-impact journals, and reputed conference papers using keyword combinations from the paper's title, abstract, and keywords to achieve meaningful outcomes. The search methodology prioritized papers that had garnered a significant number of citations, indicating their impact and relevance within the academic community. The search is also limited to publications written in English, focusing exclusively on journals as the types of content selected. The focus was on publications spanning from 2015 to 2023 to ensure relevance to contemporary research in the field. The study selection method is elaborated in the following Table 2. The proposed SLR exploits indexing databases that are Google Scholar, Science Citation Index Expanded (SCIE), Scopus, DBLP, and Association of Computing Machinery (ACM) to collect studies.

Table 2. Most Relevant Study Selection

Totally Retrieved Studies	Data Sources	Automated Filtering	Manual Filtering	Finally Selected Studies
1046	Google Scholar	526	114	114
	SCI			
	Scopus			
	DBLP			
	ACM			

Selection Process: Relevant studies are selected by removing duplicates and by employing manual reading methods. Further, the selected papers are filtered based on the survey, and application-oriented papers represent a comprehensive synthesis of existing literature on RPL and OFs in the context of the IoT. The manual reading involves a thorough examination of each document, like abstract-based reading or full article-based reading, to select the most relevant studies related to RPL-OF in IoT. This process is applied to all retrieved journal papers, resulting in a final selection of the most pertinent studies for our research. The inclusion and exclusion criteria employed to select the most pertinent studies related to the research topic are detailed in Table 3.

Table 3. Inclusion and exclusion criteria for selecting relevant papers for the survey

Inclusion Criteria	Exclusion Criteria
Papers are specifically analyzing OFs in RPL routing protocols.	Papers that are irrelevant to RPL-OF in IoT scenarios.
Studies demonstrating the application of RPL OFs in various simulated scenarios.	Papers related to RPL security, attacks, and their detection.
Publications greater than 2015.	Publications earlier than 2015.
Studies related to RPL-OF analysis on diverse network scenarios.	Studies are irrelevant to RPL-OF analysis on diverse network scenarios.
Papers from reputable databases.	Duplicate publication.
Conference papers with high quality and Citations above 5.	Conference papers with citations below 5.

The selected papers predominantly appeared in indexed journals in the field of sensors, mobile computing, communications, and IoT. Additionally, contributions published in venues sponsored by other publishers, including Springer, were observed, further enriching the diversity and breadth of the survey.

1.2.2. Finally Selected Studies

The finally selected papers predominantly appeared in indexed journals in the field of sensors, mobile computing, communications, and IoT. After careful screening and evaluation, a total of 114 studies were selected for inclusion in the survey. The selected studies cover a comprehensive range of advancements and perspectives in the OF within the smart application. The distributions of final studies utilized in this survey paper, based on the year and number of papers, are shown in Figure 2. This survey covers literature primarily published from January 2015 to May 2024, with distributions separately presented for journals to ensure a systematic and clear presentation.

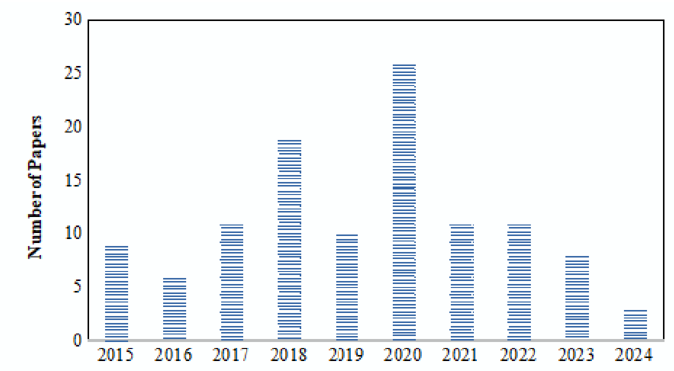

Figure 2. Year based distribution

1.3. Paper Organization

The remaining sections of this paper are organized as follows: Section 2 reviews the preliminaries of the RPL Routing Protocol. Section 3 explores the customization of OF for diverse network scenarios. Section 4 presents IoT Application-based Specific OFs. Section 5 discusses Future Research Directions for RPL applications, and Section 6 provides the Conclusion. Figure 3 shows the paper organization.

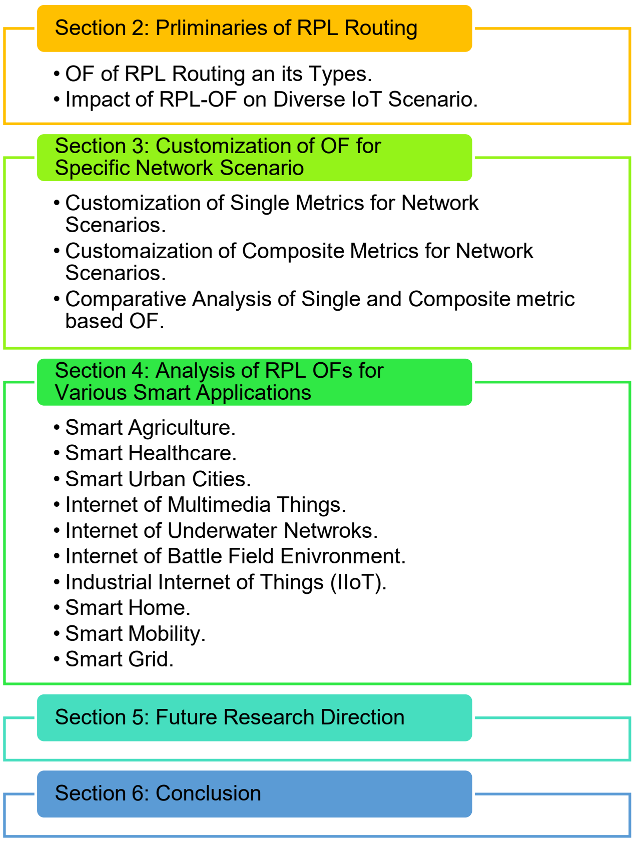

Figure 3. Paper Organization

2. Preliminaries of RPL Routing

This section addresses RQ1 by exploring preliminaries of RPL routing with its OF types and the impact of standard OFs on diverse IoT scenarios. RPL is particularly designed for the LLN environment, which offers seamless advantages when implementing IoT. The key features of RPL flexibility are DODAG, OF, rank, mode of operations, trickle algorithm, and control messages. Unique RPL advantages, such as energy efficiency, scalability, robustness, and flexibility, make it highly adoptable for IoT environments. Figure 4 shows the DODAG construction process of RPL. RPL utilizes four ICMPv6 control messages to maintain and develop the routing topology and update routing information.

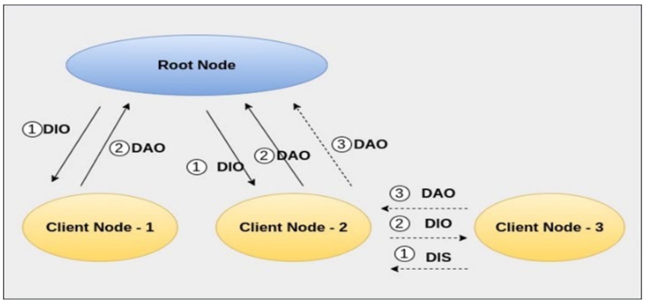

Figure 4. RPL DODAG Constuction Process

DODAG information object (DIO): The DIO packet is generated by the root to construct a new DAG and multicast through the DODAG. It enables a node to discover an RPL instance, join a specific DODAG, and select a set of candidate parents according to its OF and routing information.

Destination advertisement object (DAO): DAO messages are sent by each node to update the routing tables of their parents with prefixes of their children to build the downward routes from the DODAG root to its associated nodes.

DODAG information solicitation (DIS): A new node that does not have a route multicasts the DIS message to solicit a DIO from an RPL node. Helps locate floating and grounding DODAGs, with DIO responding to DIS transmissions.

DAO acknowledgment (DAO-ACK): This represents an acknowledgment of the reception of the DAO message sent by the DAO receiver side.

The beneficial properties of RPL are attributed to a variety of advantageous qualities. These include loop detection during packet forwarding and triggering repairs through global and local repair mechanisms [12]. While global repairs address more significant problems throughout the network, local repairs address disruptions that only affect the nodes that are directly impacted. These repair techniques enable high scalability. The RPL supports inter-node traffic flows, dynamic path selection, automatic configuration during routing, separate packet processing and routing processes, and operation over various connectivity layers. Standardization is another advantage, which improves interoperability and facilitates the integration of diverse network components [13] [14]. Additionally, RPL offers flexibility through support for different OFs, allowing customization to suit specific application requirements. Moreover, RPL's mobility ensures seamless communication for devices within the network, which preserves connectivity and dynamically optimizes routing patterns [15]. Finally, security features integrated with RPL safeguard network communications and mitigate risks associated with unauthorized access or data breaches. These properties collectively make RPL a robust and versatile routing protocol for LLNs, capable of meeting the diverse needs of IoT applications. All of these properties combine to make RPL a reliable and adaptable routing protocol for LLNs that can handle a wide range of IoT application requirements [16].

2.1. OF for RPL Routing

The OF is the process that influences the performance of routing protocols. It is the path selection process toward the root node by choosing parent nodes. The OF defines a set of policies and rules governing the route selection and optimization process [17] [18].

2.1.1.Types of RPL OF

The OF calculates the rank of the node among the DODAG versions based on a routing metric. DODAG selects parent nodes with an appropriate rank. RPL employs two standard OFs: i) OF Zero (OF0) and ii) Minimum Rank Hysteresis OF (MRHOF). Consequently, hop count serves as the default metric for OF0, while ETX is employed as the routing metric for MRHOF. ETX outperforms OF0 in performance comparison. Key terminologies within RPL include Directed Acyclic Graph (DAG), Destination Oriented Directed Acyclic Graph (DODAG), and Rank [16]. The execution of a specific application in an LLN incorporates fundamental OFs tailored to the scope or requirements of the application [19] [20]. Generally, RPL utilizes the following OFs:

OF zero (OF0): By default, OF0 utilizes hop count as a routing metric to determine the optimal parent node from among the candidate neighbour nodes. All parent nodes are potential replacements for upward traffic, and the role of OF0 is to enable nodes to connect with the parent node, offering better connectivity, thereby establishing a robust set of nodes in the network. The rank (R) metric is the heart of OF0, and the fundamental mathematical expression is as follows.

$$R_i = R_P + Min_{HRI} \quad (1)$$

Where the terms $R_i \wedge R_P$ refer to the rank of the i_{th} and parent nodes in the network. The term Min_{HRI} defines the minimum hop rank increase in the network. During the DODAG construction process, nodes must prioritize the shortest path based on hop counts towards the root nodes [21]. The rank of each node should ideally be proportional to its distance from the root node. Ranks increase downwards from the root to candidate nodes to maintain path diversity. However, OF0 is designed for LLN environments to prioritize node metrics over link quality, which potentially degrades network performance. It leads to nodes selecting paths with the lowest hop count, even if they are less reliable and prone to more retransmissions and packet loss, or even if there is a longer path with better quality and performance. Furthermore, repeatedly choosing the shortest-hop path can increase network congestion and node failures, adversely affecting network lifespan. The primary drawback of OF0 is its failure to prioritize load balancing. The HC metric would be beneficially utilized when integrated with other link metrics in a well-structured manner.

Minimum Rank Hysteresis OF (MRHOF): MRHOF utilizes the ETX metrics and chooses the paths with the lowest number of transmission values as the path toward the root node. It achieves this objective through two mechanisms: The first mechanism is termed hysteresis, which enables path switching to lower-ranked paths if they are shorter than the present path, and the second mechanism is a cost-minimization mechanism that identifies the most efficient pathway. MRHOF relies on dynamic connectivity or link metrics like ETX and rank to maintain rank stability or node metric energy. The mathematical expression for MRHOF is expressed as follows.

$$R_i(MRHOF) = min_{j\epsilon N}\left(R_j + ETX_{ij}\right) \qquad (2)$$

Where the term R_i (MRHOF) represents the MRHOF utilized by the i_{th} node, whose rank is R. The term R_j is the rank value of the j_{th} node, which is the neighbour for node i. The term ETXij is the link metric between nodes i and j. The term N refers to the total number of neighbouring nodes for node i. This metric incorporates link throughput and loss considerations while minimizing data retransmission, making it valuable for energy-efficient routing. Additionally, it supports additive metrics endorsed by the IETF to address issues associated with static metrics, ensuring optimal path selection while mitigating network churn overflow. Moreover, MRHOF makes its decision based on the link loss rate, aiming to minimize the number of transmissions to the root. In contrast, OF0 prioritizes minimizing the hop counts to the root without taking the link loss rate into account. Therefore, the advantage of using MRHOF becomes more apparent in situations where the link loss rate is elevated [22].

Energy-based OF: This metric is especially designed for optimizing the RPL routing decisions by considering energy efficiency as a primary metric within IoT and similar LLN environments. The main goal is to extend the network lifetime by preserving energy across resource-limited nodes [23]. It accomplishes this by providing preferences to the routing paths and parent nodes that require less energy consumption for packet forwarding [24]. It utilizes energy metrics for each node and link in the network. Typically, the energy-based OF takes into account factors such as energy consumption rates, battery status, and the computed energy necessary for packet forwarding. For instance, a node that has an R rank value exploits energy-based OF. The mathematical formula is expressed as follows.

$$R_i = R_P + \left(\frac{\alpha * 1}{E_R}\right) + \left(\beta * LM_{i,j}\right) \qquad (3)$$

Where the term R_P refer to the rank value of parent P and the term E_R is the remaining energy value of node i. The term $LM_{i,j}$ is the link metric utilized between node i and node j. The terms α and $\beta$are weighting factors, and their summation is equal to one. Lower energy metrics indicate that nodes or links are more energy-efficient. Unlike traditional OFs, energy-based OFs mainly focus on minimizing energy consumption. Moreover, the latency-based OFs assist in mitigating energy depletion impact and ensure nodes can operate for prolonged periods without necessitating battery replacements or recharges. Especially suitable for IoT networks where resource-limited devices are often deployed in hard-to-reach or resource-constrained environments.

Latency-based OF: It aims to optimize routing decisions based on minimizing packet transmission delays or latency. The primary goal of the Latency-Based OF is to reduce end-to-end packet delivery latency within the network [21]. It achieves this by selecting paths that offer lower latency, thereby improving the responsiveness and real-time performance of applications. It calculates latency metrics for each node and link in the network. It typically considers latency parameters that are delayed in propagation, queuing, and processing along the path. It prefers paths with minimum cumulative latency values for routing and enhances performance efficiency. Unlike traditional metrics such as hop count or energy consumption, latency-based OF prioritizes minimizing packet delivery time. Therefore, latency-based OF is critical for time-sensitive applications in which delay is the primary factor that can impact the entire efficiency and usability of the network.

Hybrid OF: It combines more than one metric and several optimization criteria to make better routing decisions. Hybrid OF incorporates diverse metrics, such as hop count, energy efficiency, latency, reliability, load balancing, and mobility, into its decision-making process [25]. This property assists in balancing multiple objectives simultaneously, resulting in the optimization of RPL routing paths. The primary intention of Hybrid OF is to enable versatile and highly adaptable routing strategies that can meet network requirement diversity. For example, a node i, N_i in the network, a hybrid OF is as follows.

$$N_i = R_P + \left(\alpha LM_{ij}\right) + \left(\frac{\beta * 1}{E_R}\right) + \left(\gamma * LM_{i,j}\right) \qquad (4)$$

The hybrid OF dynamically adjusts RPL routing decisions according to the requirements of the current network and application. Moreover, it is highly suitable for a wide range of IoT applications and network scenarios in which diverse performance metrics are essential for balanced efficiency. Improves network performance, such as reliability, energy efficiency, and responsiveness, by optimizing routes based on multiple criteria simultaneously. However, complexity in terms of computation and resource utilization is the major concern of hybrid OFs.

Custom OF: It is a specialized decision-making OF tailored to the specific requirements and objectives of a particular IoT network deployment. The main motive of custom OF is routing decision optimization by taking into account the unique requirements or specifications of the IoT deployment [26]. Generally, it can prioritize factors such as reliability, QoS, energy efficiency, latency, load balancing, or any particular performance metric that is critical to the application.

$$N_i = SA_t\left(R_P + \left(\alpha LM_{ij}\right) + \left(\frac{\beta * 1}{E_R}\right) + \left(\gamma * LM_{i,j}\right)\right) \qquad (5)$$

Where the terms $N_i \wedge SA_t$ refer to node i and the specific application type, respectively. Custom OF can assist in incorporating unique routing metrics or criteria into the decision-making of RPL routing. The specific application requirements, environmental conditions, and network constraints can be used to design the custom OF. Moreover, it provides a seamless flexibility to adapt the OF according to evolving network conditions, specific application demands, or particular technological advancements. It permits iterative routing strategy refinement and adjustment based on the feedback of real-world network performance.

2.2. Impact of RPL-OF on Diverse IoT Scenarios

The impact of RPL-OF on IoT scenarios is multifaceted, and its influencing aspects are technology support, scalability, mobility, energy efficiency, reliability, load-balancing, performance efficiency, complexity, security, QoS, adaptability, and application-specific optimizations, which are discussed in Table 4.

Table 4. Impact of Standard OFs on Diverse IoT Network Scenarios

Parameters	ETX	OF0	MRHOF	Energy-based OF	Latency-based OF	Hybrid OF	Custom OF
Technology Support	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Scalability	Moderate	High	High	Moderate	Moderate	High	Varying
Mobility	Low	Low	Moderate	Low	Low	Moderate	Varying
Load-Balancing	Low	Low	Moderate	High	Low	High	Varying
Reliability	High	Moderate	High	Moderate	Moderate	High	Varying
Performance Efficiency	Low	Low	Low	Moderate	Moderate	High	High
Security	Low	Low	Low	Low	Low	Low	Varying
QoS	High	Low	High	Moderate	High	High	Varying
Energy Efficiency	Moderate	Low	Moderate	High	Low	High	Varying
Complexity	Moderate	Low	Moderate	High	High	Very High	Varying
Adaptability	High	High	High	High	High	High	Low
Application Specific Optimization	Simple IoT networks	Highly Dynamic IoT	Reliable IoT networks	Energy-constrained IoT devices	Real-time IoT applications	Versatile and multi-dimensional optimization	Customized IoT deployments

3. Customization of OF for Specific Network Scenarios

Apart from the standard routing metrics outlined for RPL, numerous other routing metrics have been introduced in recent research aimed at improving various networking aspects. Though the OFs based solely on hop count may yield paths with fewer hops and lower energy consumption, they can also create bottlenecks, hinder load balancing, and fail to ensure high-quality routes, unlike MRHOF. Conversely, MRHOF prioritizes reliability over energy efficiency, potentially consuming more energy but offering more dependable routes. Therefore, enhancing OF metrics by introducing new metrics within the OF makes it better adapt to the varied demands encountered in LLNs. These improvements address particular concerns such as enhancing reliability, energy efficiency, quality of service, and load distribution. Customization of OF for specific network scenarios is divided into two types: single metric-based and composite metric-based, as shown in Figure 5.

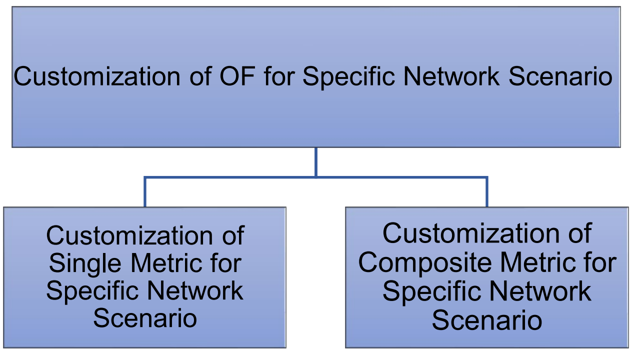

Figure 5. Customization of OF for Specific Network Scenario

3.1. Customization of a Single Metric for a Specific Network Scenario

Customization of a single metric for a specific network scenario is categorized into different types that are energy efficiency, load distribution or balancing, QoS aware, mobility-based, and congestion aware, as shown in Figure 6.

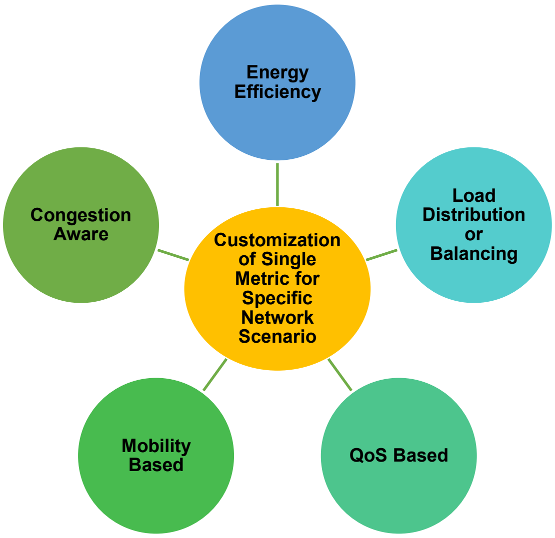

Figure 6. Customization of a Single Metric for a Specific Network Scenario

3.1.1. Energy Efficiency-based Customization

In [21, 24], an MRHOF based on an energy metric is discussed. As the conventional OF relies on link metrics as the sole criterion (such as MRHOF based on ETX) for choosing the next hop toward the destination, this MRHOF (energy) employs a node metric. Nodes periodically verify the availability of a reliable link to the root during network operation, resulting in increased energy consumption. To address this concern, MRHOF selects parents with sustained high energy levels. Contrary to MRHOF combined with ETX, employing energy in MRHOF results in increased packet loss and delay. However, it balances energy distribution across all nodes while maintaining transmission accuracy, potentially extending the network's lifetime.

3.1.2. Load Distribution or Balancing-based Customization

Having more children for a parent leads to increased overhead and uneven load distribution, which results in faster energy depletion compared to other potential parent nodes. Addressing this issue, a load-balanced OF (LB-OF) was introduced [27] to mitigate data traffic imbalances by considering the number of children for each potential parent node rather than just ETX. The parent with the fewest children is selected as the preferred parent, thereby achieving load balance by reducing the number of children for overloaded bottleneck nodes. Consequently, most children will opt for another preferred parent with a lower rank, resulting in a reduced number of children. Simulation results demonstrate that LB-OF outperforms MRHOF and OF0 in terms of packet delivery rate, balanced power consumption, lifetime balance, and the number of children per node. However, the main drawback of LB-OF is that the number of children cannot indicate the traffic load each node forwards because each node may forward a different traffic flow size.

3.1.3. QoS-based Customization

QoS performance metrics play a crucial role in assessing the effectiveness and suitability of routing paths for various applications and network conditions. QoS metrics ensure that the network can meet the specific requirements of applications in terms of reliability, latency, packet delivery, and other performance parameters. Among these, network throughput serves as a pivotal QoS metric. In [28], researchers introduced a QoS metric concentrating on residual throughput to establish a traffic-aware OF (TAOF). This TAOF utilizes a novel RPL metric called Packet Transmission Rate (PTR) to gauge the load assigned to each node. The PTR reflects the number of packets forwarded by each node within a specific time frame.

3.1.4. Mobility-based Customization

RPL exhibits poor performance in terms of throughput and adaptability to network dynamics. The survey [29] on RPL mobility observed that the control traffic required to maintain up-to-date routing tables has a significant negative impact. More spectrum-efficient protocols are needed to address potential scenarios for LLNs that require increased mobility of nodes. To address this limitation, the study [30] introduced a Back Pressure RPL (BRPL) mechanism for sensor nodes aimed at accommodating mobility and time-varying data. They utilized two lightweight algorithms, Quick Beta and Quick Theta, to manage node mobility and fluctuations in data traffic. The primary objective is to ensure interoperability with RPL and backpressure routing. However, they did not consider energy consumption, where further investigations are needed to achieve a comprehensive understanding.

3.1.5. Congestion-Aware Customization

The congestion significantly impacts the network performance, which leads to packet loss, increased latency, and reduced overall throughput. To address these challenges, congestion-aware enhancements in routing metrics have been developed to optimize routing decisions and improve network efficiency under congested conditions. A study [31] introduced a new RPL routing metric called Buffer Occupancy (BO) for reducing the packet loss caused by buffer overflow during congestion. Additionally, they proposed Congestion-Aware OF (CA-OF) to efficiently manage congestion by selecting less congested paths, by combining both metrics ETX and BO. By incorporating these enhancements, RPL networks can maintain optimal performance even under varying traffic conditions. The work in [32] proposes Expected transmission count remaining energy (ETXRE) that incorporates two fundamental routing metrics, such as link-based routing metrics like ETX and the remaining energy of nodes in the network. Consolidation of these two routing metrics has proved to have significant potential to rectify the excessive counts of ETX and the remaining energy performance constraints. Thus, relying solely on these single metrics may not be efficient, as some metrics do not account for the link quality of the network and fail to meet all QoS requirements across various applications. However, relying on a single metric within an OF can impose constraints on routing performance, resulting in suboptimal path selections. Thus, several studies have suggested combining multiple metrics to fulfill requirements in LLNs. Therefore, integrating multiple routing metrics of various types into a unified composite can enhance the quality-of-service performance [33].

3.2. Customization of Composition Metric for Specific Network Scenario

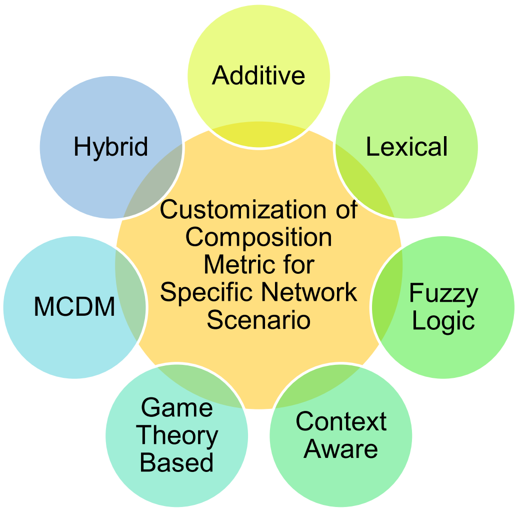

Figure 7. Customization of Composite Metric for Specific Network Scenario

RPL metric composition approach involves combining individual metrics into a composite value or rank that represents a specific property of a network based on calculations of certain network parameters. Customization of composite metrics for specific network scenarios is depicted in Figure 7. RPL supports the utilization of single or multiple routing metrics, which can be provided as static or dynamic values. Configuring RPL metrics enables enhancements to various aspects of network performance to accommodate the requirements of diverse applications. This optimization involves the utilization of single or multiple metrics to make optimal routing decisions. However, designing an efficient RPL composite routing metric tailored to a specific application remains a challenging task. The selection of the optimal OF is left to the user based on the specific application requirements. Combined routing metrics must be well-defined, non-antagonistic, orthogonal, monotonic, scalable, and isotonic. The monotonic property guarantees a loop-free topology, while the isotonic property ensures that the source selects the optimal path for transmitting data to the destination.

3.2.1. Additive Metric Composition

In the additive approach, both routing metrics must share the same order relation to ensure the resulting composite additive routing metric is meaningful. The strict monotonicity property of the additive routing metric holds for any combination of routing metrics that are strictly monotonic or a mix of strictly monotonic and monotonic. For instance, the Hop count is combined with ETX's primary routing metric. The weight factors are applied to each primary routing metric. These weights can be adjusted according to the user's preferences and the requirements of the specific application in use [34]. The additive composition follows the equation form as given below:

$$R_M = (w1 * HP) + (w2 * ETX) \qquad (6)$$

Where the term R_M refer to the routing metric, and the term HP is the hop count. The terms w1 and w2 are weighting factors, w1+w2=1. According to the application requirements, the weighting factor is used to give high importance to the metric, which is highly preferred in the network. For example, in [38], a congestion avoidance mechanism for a multipath routing protocol was developed using composite routing metrics. Specifically, they designed a routing metric for RPL called DELAY ROOT that minimizes the average delay to the DAG root. It also successfully alleviated network congestion by distributing a large amount of data traffic across different paths and reducing packet delay. However, the additive composition assumes that all metrics have equal importance, which may not always be the case. Assigning appropriate weights to each metric can be subjective and challenging.

3.2.2. Lexical Metric Composition

In the lexicographic approach, a composite metric is formed based on the ordering of preferences among the individual metrics. The first metric takes precedence, and the path with the highest or lowest value for that metric is prioritized for data transmission. If there is a tie, the second metric is considered, and so forth [35]. For example, in the study [36], tie-breaking metrics are employed within the framework of a multi-sink RPL topology. The tie-breaking metrics considered include available bandwidth, ETX, delay, and MAC-layer buffer occupancy. Unlike the additive metric composition, the lexical approach / This combination method provides clear metric prioritization. However, it is important to note that not all reference routing metrics can be effectively validated using this lexical approach.

3.2.3. Fuzzy Logic Metric Composition

Fuzzy logic is a mathematical approach that deals with uncertainty and imprecision, which allows for degrees of truth between 0 and 1, enabling a more flexible and nuanced representation of data. Fuzzy logic is integrated into RPL to create composite metrics by considering the uncertainty and imprecision inherent in network conditions and metric measurements. It utilizes linguistic representation of metrics and rules for more intuitive and human-like decision-making processes. For example, instead of using precise numerical values for metrics such as link quality or energy consumption, fuzzy logic represents them using linguistic terms like good, average, or poor, along with fuzzy sets and membership functions to quantify these terms. The membership function consolidates multiple independent variables into a single outcome. Several membership functions, such as sigmoid, Gaussian, and triangular, are specified within fuzzy systems for utilization in both the fuzzification and defuzzification stages. Nonetheless, the prevalent form of membership employed in fuzzy systems is the trapezoidal function [37]. The data are categorized using linguistic variables, and their correlations are established accordingly [38]. Fuzzy logic defines a set of rules that define how individual metrics contribute to overall route evaluation, considering factors such as metric importance and interaction [39]. Table 5 outlines the correlation between these linguistic variables to compute the output variable. A small ETX value coupled with low energy consumption indicates an enhanced quality of the path. The OF, based on a combination of ETX and energy consumption called OF-EC, facilitates enhancements in RPL performance regarding PDR and overhead. Moreover, this novel metric facilitates the equalization of energy consumption among nodes across the network.

Table 5. Example of Fuzzy Rule

ENERGY CONSUMED	NUMBER OF HOPS	ETX	QUALITY THE ROUTE
LOW	Low	Low	High
HIGH	Medium	Low	Medium
HIGH	High	Low	Medium
MEDIUM	Low	High	Medium
HIGH	Medium	Medium	Low
LOW	High	Medium	Medium

Similarly, in the study [40], the latency and reliability requirements of LLNs are addressed by designing a power control and cross-layer-based RPL OF using a fuzzy logic-based approach. The work in [41] enhances the RPL efficiency by choosing an optimal route with the assistance of a binary gray wolf optimization strategy. It chooses the best parent in the RPL routing procedure based on OF during the phase of tree construction. It exploits fuzzy logic and the Binary gray wolf optimization to construct the OF. The work in [42] also introduces a fuzzy logic-based OF to enhance the RPL routing reliability in LLNs. The study in [43] provides an in-depth overview of current literature pertaining to the topic related to RPL-OF. The primary objective of this study is to provide a comprehensive analysis that incorporates the combination of innovative metric development and fuzzy logic application strategies for OF metrics. However, implementing fuzzy logic-based composite metrics can add complexity to routing algorithms, demanding more computational resources and expertise for design and maintenance.

3.2.4. Context Awareness Metric Composition

The context-aware OF selection improves routing performance in RPL-based IoT networks by routing data packets based on the surrounding situation [45]. The Context-awareness composition is a powerful and salient technique that empowers intelligent interactions between appliances and devices. Contextual awareness involves treating contextual information as a valuable attribute and can be divided into several groups of consciousness, including Resource Health, Privacy, QoS, Information, and Mobility. Various techniques are used to integrate context-aware metrics, such as weighted aggregation, fuzzy logic, machine learning, or rule-based reasoning [45]. For instance, the study [37] proposed the context-oriented OF (COOF) to address the challenges encountered in dynamic IoT-based smart city networks. The OF is defined using three routing metrics based on a fuzzy logic technique.

3.2.5. Game Theory-based Metric Composition

Further enhancements to the RPL OF involve metric construction based on game theory. These enhancements primarily address congestion control in the LLNs. Several routing metrics are utilized to calculate the rank of nodes in the network. Each child node employs a possible game-theory-based strategy to select the best parent node. The study [46] addressed the network congestion problem between parent nodes and child nodes in RPL-enabled networks by designing a parent-change procedure using a game theory strategy, through which the child nodes change next-hop neighbours toward the sink.

3.2.6. MCDM Metric Composition

Similar to the game theory, the parent selection process can be developed as a multi-criteria decision-making (MCDM) problem by combining various routing metrics. In [47], congestion-aware RPL (CoAR) was designed for dynamic and high traffic load using a resource-control-based congestion alleviation method, an adaptive congestion detection mechanism, and an MCDM technique for parent selection, which utilizes the multiple routing criteria such as network congestion, link quality, energy efficiency, and node proximity. A Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) is utilized as an aggregation method in MCDM. TOPSIS integrates multiple metrics to formulate an OF, positing that the optimal choice should exhibit the shortest distance to positive ideal solutions and the greatest distance from negative ideal solutions, thereby enhancing network resilience, efficiency, and adaptability.

3.2.7. Hybrid Composite Metrics

In RPL, an OF specifies a set of metrics for best parent and path selection, thereby assuring a quick route to the destination. A composite metric consolidates more than one metric for this optimization. For instance, the work in [48] proposes a novel OF-FZ that exploits four metrics for making better routing decisions. Initially, fuzzy Logic is employed to consolidate the metrics like hop count, ETX, delay, and node remaining energy to obtain a single decision metric score referred to as Quality Assurance (QA). During RPL routing, a neighbour node that has the highest QA score is selected as the best parent. The work in [49] introduces an energy-aware routing-based OF strategy using the novel metric, which works based on three aspects: residual energy, threshold, and quality index. Similarly, the work in [50] introduces an energy-efficient OF for light control in smart agriculture. Although numerous RPL-OFs on distinct aspects of routing and data exchanges, some base-level challenges, that is, instant negative impacts of choosing the best possible path and the absence of measuring to observe the node's dynamic conditions, still exist. Therefore, the work in [50] introduces a strategy called RI-RPL, based on the novel metric, along with the exploitation of reinforcement learning to address the constraints of RPL in IoT effectively. Similarly, the work in [51] introduces a congestion-aware RPL protocol that prevents network congestion with the assistance of a Q-learning algorithm. It improves the QoS by effectively balancing the load between nodes in the network. A novel lightweight routing protocol in [52] improves the performance of the Internet of mobile things by including a fuzzy logic strategy in LLNs. It takes into account the multiple metrics that are receiving Euclidean distance, Signal Strength Indicator (RSSI), Hop Count, and ETX to build into the fuzzy interface system for the mobile IoT nodes.

3.3. Comparative Analysis of Single and Composite metric-based OF

In Table 6, a detailed comparative analysis is presented, focusing on single and composite metric-based OF within the context of the study. This analysis aims to provide insights into the effectiveness and applicability of different OF approaches in optimizing network performance and routing efficiency. By considering various parameters simultaneously, composite metrics better adapt to diverse network conditions and provide more nuanced routing decisions for varied application scenarios. Table 6 results show that the energy-efficient OFs are highly suitable for specific IoT applications that necessitate resource-constrained OFs [54-55] [58-59]. Some OF the customizations in [56-57] and [60-73] consider multiple metrics for enhancing the RPL-OFs, and their IoT adaptability characteristics are also different.

Table 6. Comparative Analysis of Single and Composite OF

OF	Metric Category	Metrics	Topology	Energy efficiency	QoS	Performance	Complexity	Application Adaptability	Integration Ability
OF-Energy [54]	Single	Remaining Energy	Star and Tree	Yes	No	Moderate	High	Low	No
OF-Fuzzy [55]	Composite	Delay, Energy, ETX	Tree	Yes	No	Moderate	Very High	High	Yes
OF-FL [56]	Composite	Delay, Hop count, ETX, LQL	Random	No	Yes	High	Very High	High	Yes
FM-OF [57]	Composite	ETX, Hop Count, and RSSI	Linear	No	No	Low	High	High	No
OF0 and ETX [58]	Single	Comparison b/w Hop count and ETX	Random	Yes	No	Low	Low	High	Yes
OF-EC [23]	Composite	Hop count, ETX, and Total Energy Consumption	Random and Grid	Yes	No	Moderate	High	Low	Yes
SCAOF [59]	Composite	Energy-aware	Grid	Yes	Yes	High	High	High	Yes
CMOF [40]	Composite	Estimated latency and ETX	Hybrid	No	No	Moderate	Very High	Low	No
ERAOF [60]	Composite	ETX, Energy consumption (EC)	Grid	Yes	No	High	Very High	Low	Yes

OFQS [61]	Composite	Delay, ETX, power state	Random	Yes	No	Low	High	High	Yes
CoAR, CoA-OF [47]	Composite	ETX, QU, RE, and tie-breaking, NI.	Grid	Yes	No	High	Very high	Medium	Yes
DQCA-OF [62]	Composite	Hop Count, ETX, Consumed Energy	Random	Yes	Yes	High	Very high	High	No
CA-OF [31]	Composite	Buffer Occupancy and ETX	Tree	Yes	No	Moderate	High	High	Yes
CA-RPL [35]	Composite	ETX, Rank, Delay, and no. of received packets	Grid	No	No	Low	Low	Low	Yes
AHP-OF [63]	Composite	ETX, HC, and Residual Energy	Random	No	No	High	High	High	No
CAOF [64]	Composite	Remain energy, queue utilization, CARF	Tree	Yes	No	Low	Medium	High	Yes
WRF-RPL [65]	Composite	Remaining energy and the count of parent nodes	Random	Yes	No	Moderate	Medium	Medium	Yes
QU-RPL [66]	Composite	Queue factor, hop count, and ETX metric	Tree	No	No	High	High	High	Yes
OF-FZ [67]	Composite	hop count, ETX, delay, and RE	Random	Yes	No	High	High	Low	Yes

LA-OF [68]	Single	ETX	Grid	Yes	No	Moderate	Low	Medium	Yes
QWL-RPL [69]	Composite	Node workload and queue status	Random	No	No	High	High	High	Yes
EMOF [70]	Composite	Energy consumption, hop count, and ETX	Random and grid	Yes	Yes	High	Very High	Low	Yes
ELITE [71]	Single	Strobe per Packet Ratio (SPR).	Random	Yes	No	Moderate	Low	Low	No
PEOF, PEOF2 [72]	Composite	ETX and remaining energy	Grid	Yes	No	Low	Low	Low	No
SEEOF [73]	Composite	ETX and Estimated Remaining Life Time (ERLT)	Mesh	Yes	No	Low	Medium	High	Yes

4. Analysis of RPL OFs for Various Smart Applications

This section addresses research question 3 by briefly analyzing the OFs tailored to specific smart IoT applications. Each IoT application has unique requirements and constraints, necessitating customized OFs to optimize performance and efficiency. The IoT application-specific OF defines the key goals and metrics for evaluating the performance of an IoT system. In this section, researches on various IoT application-specific OFs are explored, as shown in Figure 8. The various functions developed to address the unique requirements of different IoT applications across industries such as healthcare and agriculture are explored.

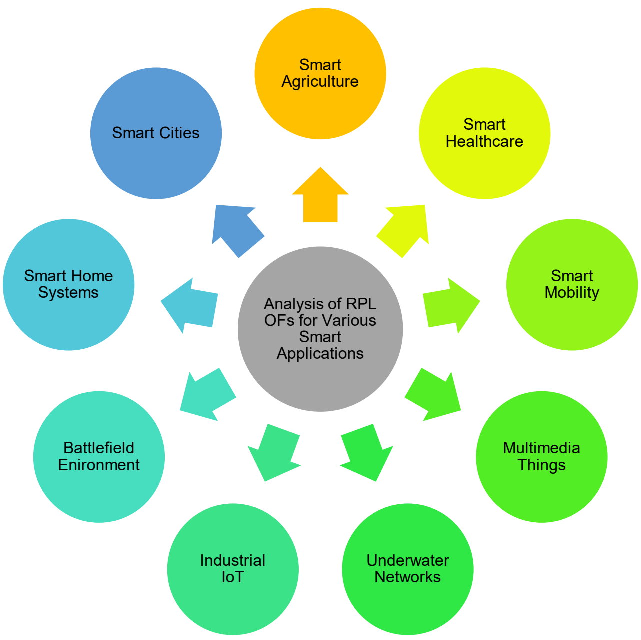

Figure 8. Smart IoT Application

4.1. Smart Agriculture

IoT has revolutionized agriculture by addressing numerous complexities and challenges. Extensive work has been conducted on IoT technology in agriculture to develop and maintain smart farming solutions. By leveraging RPL-IoT protocols, farmers can communicate more conveniently and make more informed decisions to improve crop growth and cultivation, as highlighted in [74]. The study also provided an extensive overview of current and continuing advances in IoT agricultural applications, devices/sensors, communication protocols, and many innovative technologies. The study [75] introduced a Partition Aware-RPL (PA-RPL), a novel OF aimed to optimize the generated routing DODAG by considering the spatial division of the monitored farm. It incorporates the physical partitioning into the construction of the DODAG. The PA-RPL constructs a routing topology that enables efficient in-network data aggregation, accounting for the actual division of the farm into parcels or sectors. Hence, data traffic is significantly reduced throughout the network, and an energy saving of up to 40% compared to standard RPL. Another research [76] designed a Collaborative Beamforming (CB), where multiple clusters of sensor nodes create unique Sensor-Based Virtual Antenna Arrays (SVAA). These SVAA transmit the collected data to various UAVs involved in different tasks. The study [77] concentrated on precision agriculture (PA) for monitoring a coffee plantation. It aimed to determine the optimal topology and characteristics to balance between low cost, reliability, and maximizing battery lifetime in a mesh WSN for the IoT environment. The PA results indicated that the circular topology using the HOP metric exhibited the lowest energy consumption, surpassing the grid topology by 15% and the tree topology by 30%. These findings underscore the importance of enhancing RPL metrics evolution and motivating topology network management. Moreover, the significance of RPL-OF in smart agriculture maximizes efficiency, reliability, and scalability. Each work employs different RPL-OF or metrics according to the specific requirements of diverse agricultural deployments. For instance, some scenarios may prioritize energy-efficient routing, while others may focus on shrinking delay or improving data throughput. Such flexibility necessitates a unique RPL-OF, which is highly suitable for a wide range of smart agriculture use cases.

4.2. Smart Healthcare

The surge in Smart healthcare is gaining momentum due to the abundance of application contexts. IoT plays a significant role in the evolution of healthcare into smart healthcare. This transformation entails several key aspects: ensuring timely delivery of treatment to the right individuals, facilitating accurate diagnosis and treatment by clinicians, efficient exchange of information among stakeholders, centralized availability of data, timely notifications to engage patients in their treatment, extending healthcare services to remote areas through cost-effective models, and enhancing efficiency by minimizing waste and operational costs [78]. The research [79] proposed a Priority-based Energy-Efficient Routing Protocol (PEERP) designed for reliable data transmission in healthcare via IoT. Here, the health data is classified into Emergency Situations and Vital Health Data, each allocated with appropriate priorities. In [80], the RPL-based routing protocol framework enhanced energy efficiency in WSNs by accommodating both static and mobile nodes. Efficient OF in the framework contributes to intelligent healthcare advancements while minimizing total energy consumption and controlling traffic volume while maintaining PDR levels. The study [81] examined the ETX and OF0 across varying network densities and topologies, including grid and random topologies with different Receiver (RX) configurations. The OF0 demonstrates superior performance in terms of PDR while maintaining a comparable power consumption rate to ETX. Therefore, OF0 can be strongly recommended for the design of a WSN tailored for healthcare, especially in an Intensive Care Unit (ICU). However, the works lack the design of a highly interoperable OF, which can support diverse healthcare use cases. RPL-OF is designed to accomplish seamless performance efficiency with other IoT protocols and standards, assuring compatibility and easy integration within broader smart healthcare systems. This customization is very crucial to developing more comprehensive and cohesive healthcare routing solutions.

4.3. Urban Smart Cities

Urban smart cities represent another prominent application of IoT. They encompass automated transportation, smart monitoring, water supply management, smart energy systems, urban security enhancements, and environmental tracking, among other IoT applications. In [82], a Multi-DODAG model is introduced to enhance efficiency and reliability in smart cities. In [83], the introduction of DYNAmic multiple RPL InstanceS for multiple ioT ApplicatIon (DYNASTI) aims to enhance the dynamism and flexibility of smart city applications by effectively managing multiple RPL instances. DYNASTI facilitates the support of sporadic applications, concurrent implementation across multiple instances, and adaptation to critical and sporadic application requirements. In another study [84], a novel hybrid ad-hoc routing protocol framework is proposed utilizing RPL for operating in both Mobile Crowd Sensing (MCS) and WSN environments. The objective of this framework is to enhance network longevity and improve QoS by addressing issues such as hot spots, low data delivery rates, and high end-to-end delays in smart city applications. However, no unique mobility-aware OFs are proposed in the existing works. Generally, urban smart city environments are highly dynamic, with varying network conditions owing to node mobility, link interferences, and environmental changes. The RPL-OF should adapt to these dynamic conditions and maintain optimal performance by ensuring continuous and reliable communication among the nodes and devices.

4.4. Internet of Multimedia Things

The Internet of Multimedia Things (IoMMT) refers to interconnected multimedia nano-devices integrated with communication networks and the Internet [85]. In recent years, there has been a significant increase in multimedia traffic, requiring multimedia devices with high processing power and memory to handle the extensive data flow. However, extending the lifetime of IoMMT networks is a critical concern, as the high volume of multimedia data increases traffic routing demands compared to scalar data. In the study [86], a new variant of RPL for the IoMMT was proposed, which considered the remaining energy of nodes in routing IoT traffic to enhance network resilience and balance multimedia traffic among routers. This approach addressed the problem of reduced network lifetime due to high data volume, resulting in a 34% increase in node availability during the network's lifetime compared to standard RPL. Moreover, total energy consumption remains nearly unchanged compared to ETX-based RPL. In [87], a QoS-aware OF based on free bandwidth was introduced in an enhanced version of the RPL protocol known as FreeBW-RPL. This routing protocol selects a preferred parent node based on the maximum available bandwidth in its vicinity along the network path. Thus, FreeBW-OF effectively alleviates congestion issues by dynamically switching to less congested paths.

In [88], a multipath variant of RPL called MP-RPL was introduced, utilizing the multi-parent feature to establish multiple end-to-end paths with varying qualities based on radio link quality assessments. They enhanced video traffic delivery for IoMT-based Wireless Multimedia Sensor Network (WMSN) applications by utilizing these constructed paths simultaneously while considering video traffic differentiation according to priority levels. Notably, Multipath techniques mitigate network instabilities. In [89], a novel OF for RPL, named OF2, was introduced, which incorporates a composite metric combining the residual energy of a parent node with the energy that a neighboring node can transfer to the parent based on the Wireless Power Transfer (WPT) concept. Another study [90] introduced a multi-instance version of RPL (MI-RPL) with Nodes Disjoint (ND) and Links Disjoint (LD) variants to enhance the transport of compressed video, composed of two types of frames with different priorities by delivering each frame type on its corresponding instance. However, it is still in its infancy stage, and conventional research works cannot create adaptive RPL-OFs that can respond to varying conditions in realistic IoMMT and maintain optimal routing strategies. Hence, the development of adaptive OFs can solve the existing gaps by dynamically responding to changing network conditions, traffic patterns, diverse application requirements, and constraints. This enhancement will support robust multimedia solutions and increase the demand for IoMMT in various sectors.

4.5. Internet of Underwater Networks

With a significant portion of the Earth's surface covered by oceans, it has become inevitable to expand the concept of the IoT to oceanic areas, leading to a rapid emergence in the digital world [91]. The Internet of Underwater Things (IoUT) combines the internet, embedded sensors, and cutting-edge tracking technologies to sense and respond to underwater environmental conditions. IoUT devices are constrained by limited resources such as energy and computational capacity. It exhibits diverse characteristics, including various communication and tracking technologies, different energy harvesting models, dynamic network density, diverse localization methods, and complexity in battery recharging [92]. Underwater wireless sensor networks are increasingly applied in tasks like tactical surveillance and pollution monitoring. They face challenges like high propagation delay, limited bandwidth, and high error rates due to their reliance on acoustic signals for communication. To address these issues, the RPL routing protocol offers multiple upward path options and path repair methods. In a recent study [93], a hop interval-based method for deciding the Mode of Operation (MOP) of intermediate nodes was proposed to enhance the reliability of downward paths. The study [94] enhanced the OF to solve routing issues in underwater environments by considering multiple routing metrics such as hop count, ETX, and energy factor. The Underwater Adaptive RPL process facilitates energy-balanced routing across underwater devices. Network traffic is distributed among multiple parent nodes with superior rank values, thus enhancing network lifetime while maintaining communication reliability. There is no effective OF with accurate localization and node positions, which are very essential for many IoUT applications. Novel OFs that can integrate localization information to enhance routing decisions and maximize network performance need to be developed in the future.

4.6. Internet of Battlefield Environment

Within military settings, IoT technologies offer novel avenues for overseeing and conducting battlefield activities by linking together combat gear, soldier gadgets, and additional resources on the battlefield. This fusion of IoT with military networks is denoted as the Internet of Battlefield Things (IoBT). In an IoBT framework, the interconnectivity among soldiers' wearable devices and various IoBT components, including versatile sensors, unmanned vehicles, and aerial drones, holds considerable importance in executing mission-critical operations on the battlefield [95]. It facilitates real-time data sharing and communication among soldiers, vehicles, weapons, guided missiles, and other military equipment, enabling faster and more accurate decision-making on the battlefield. Moreover, in addition to enhancing situational awareness and decision-making, IoBT contributes to reducing casualties and improving soldier safety. Overall, IoBT signifies the advancement in military technology with the potential to revolutionize military operations. However, it also raises notable ethical and security concerns, as interconnected devices and networks may introduce vulnerabilities and risks for civilians and soldiers. The study [96] presents several challenges of IoBT, including compatibility, scalability, security, human factors, and power consumption, among others. To tackle path selection issues in the IoBT environment, a study [97] proposed a routing path selection approach integrating joint optimization in IoBT, considering both nonuniform node distributions and location-dependent data generation probabilities. The research [98] assessed the performance of the RPL routing protocol for military applications within hierarchical network topologies by evaluating performance metrics like control packet overhead, power usage, and packet delivery ratio across different packet error rates. However, the conventional solutions fail to incorporate multi-context information in RPL-OF design, resulting in reduced performance. Developing multi-context aware OFs can adjust routing decisions according to the current mission of the surveillance system, threat activities, and environmental conditions. Novel research works are needed to explore how RPL-OF can include multiple context-awareness in optimizing routing for various battlefield scenarios.

4.7. Industrial Internet of Things (IIoT)

IIoT represents a new perspective on IoT within the industrial domain by automating smart objects to sense, collect, process, and communicate real-time events in industrial systems. The primary aim of IIoT is to attain heightened operational efficiency, elevated productivity, and improved management of industrial assets and processes. This objective is accomplished through various means such as product customization, intelligent monitoring applications for production floor shops and machine health, as well as predictive and preventive maintenance of industrial equipment. IIoT empowers manufacturers and other industries to capture real-time data from equipment, machines, and processes, analyze it, and make informed decisions based on the insights gained [99]. One of the key advantages of IIoT is its capability to enable companies to monitor their industrial processes and equipment in real-time by collecting data on various aspects of process or machine performance, identifying inefficiencies, reducing downtime, and optimizing operations. Unlike IoT, industrial applications within the IIoT sphere are distinguished by rigorous communication demands concerning reliability and latency [100]. The research presented in [101] introduced an energy-efficient routing protocol tailored for the UAV cloud. The study [102] introduced a load-balancing approach for 6TiSCH networks, known as the traffic-aware RPL method. By predicting the impact of routing decisions for each device, this method enhanced the deterministic nature of IIoT wireless networks. The study [103] introduced a novel routing protocol termed Resource-Aware and Reliable OF (RAROF), which optimizes routing paths by considering a duty cycle of the node, link quality, energy status, and resource availability. Additionally, a new routing metric called the node vulnerability index (NVI) was developed to determine the vulnerable nodes in terms of energy depletion. However, IIoT applications often necessitate real-time or near-real-time data routing to process the monitoring and control information. The RPL-OFs should satisfy the real-time IIoT requirements by giving priority to low-latency routes and ensuring timely data delivery based on the use case type.

4.8. Smart Home

Smart Home technology with the IoT has revolutionized modern living. Smart homes leverage IoT devices and connectivity to offer unprecedented convenience, security, energy efficiency, and comfort for residents. These homes are equipped with diverse IoT-enabled devices, including smart thermostats, door locks, security cameras, appliances, entertainment systems, and lighting systems. The IoT smart home system (IoTSHS) enables the control of household appliances via internet-based communication or connectivity and generates alerts for unexpected events. Smart home functions can be remotely managed through various applications. This smart home system offers remote control to individuals who may not be able to use a smartphone to manage their appliances, including those with special needs and elderly individuals with limited education [104,105]. The study [106] introduced a smart home architecture based on 6LoWPAN, comprising multiple sensor nodes connected to a sink node. The RPL routing protocol facilitates communication between these sensor nodes. The study [107] developed HRPL as an enhancement to the RPL protocol to reduce redundant retransmissions, which contribute to routing overhead. The work introduced the T-Cut Off Delay to establish a delay limit and the H field to respond to actions taken within this delay. Although numerous RPL-OFs are presented in smart home environments, they fail to validate their solutions through extensive experimentation. Hence, there is a need to include rigorous simulations that can offer real-world trials to test the effectiveness and feasibility of novel RPL-OF by assuring it performs well or not in practical smart home settings.

4.9. Smart Mobility

Smart mobility is a forward-looking approach to transportation that utilizes advanced technologies and innovative strategies to optimize mobility systems. It has the potential to revolutionize urban planning and logistics for transporting goods and people worldwide. Such mobility services are essential for providing citizens and governments with congestion-free, environmentally friendly, and sustainable transportation options [108]. The primary objectives of intelligent mobility include alleviating traffic congestion, reducing air and noise pollution, enhancing safety, increasing travel speeds, and lowering travel costs across various transportation modes. Thus, the integration of emerging technologies into current transportation systems and the advancement of smart mobility solutions enable real-time data collection, monitoring, and management. However, the primary concern within mobile networks revolves around ensuring QoS while accommodating mobility requirements. A study [109] tackled this challenge by devising a mobility management approach within RPL (mRPL) through the development of an optimization algorithm. This research introduced a mobility-aware, energy-efficient parent selection method using the firefly optimization algorithm to facilitate the seamless movement of nodes in RPL. In response to these issues, a study [110] introduced an enhanced iteration of the RPL routing protocol, termed A Reliable and MObility-aware RPL (ARMOR). It incorporates a novel routing metric called Time-to-Reside (TTR) and implements a neighbour table replacement policy to optimize parent selection. This strategy retains and replaces more favorable parent candidates in the table while removing nodes that can no longer establish connections to the sink. Another study [111] addressed the increased packet loss in mobile nodes within the RPL protocol by introducing a mobility-aware RPL (MARPL) protocol, which improves performance in networks with mobile nodes. In [15], a novel approach was introduced to ensure uninterrupted connectivity for mobile nodes in RPL. This method involves the parent node utilizing an additional field in RPL's control packets to identify mobility and instruct the mobile node to conserve its energy, thereby reducing network overhead. Moreover, more effective and advanced RPL-OFs are crucial to supporting the diverse and evolving needs of smart mobility applications, ultimately contributing to more connected and convenient routing solutions.

4.10. Smart Grid

The smart grid is a significant evolution in the traditional electrical grid that incorporates advanced digital communication technology. Unlike the conventional grid, the smart grid is a bi-directional network that facilitates real-time monitoring and control, fault detection, integration of renewable energy sources, and enhanced consumer participation. An Advanced Metering Infrastructure (AMI) is a fundamental component of the smart grid for two-way communication between utilities and consumers. AMI networks consist of millions of endpoints, such as smart meters, distribution automation elements, and home area network (HAN) devices. These endpoints are typically interconnected using a combination of wireless and power-line communications. In AMI networks, links between devices often face challenges like high packet loss rates, low bandwidth, and instability due to unplanned deployments and low-power link-layer technologies [112]. RPL is applied in AMI systems to facilitate communication between devices like smart meters, sensors, and control systems. However, RPL faces challenges due to high network density, which causes RPL scalability issues by increasing control message overhead and potential network congestion. In response to these challenges, the study [113] proposed OFQS to address the limitations of RPL, whose main OFs and associated metrics do not support Quality of Service differentiation. OFQS is designed with a tunable multi-objective metric including delay, remaining energy in the battery nodes, and the dynamic quality of communication links. Another study [114] introduced CRB-RPL, a Receiver-based Routing Protocol for Communications in Cognitive Radio radio-enabled smart Grids. This protocol aims to meet real-time latency requirements and achieve energy efficiency. However, the RPL-OFs fail to interoperate with smart grid legacy systems, which are very crucial for their seamless integration and information exchange.

Table 7 provides an overall analysis of the study on IoT applications leveraging RPL OFs, detailing the methods or algorithms utilized, the OFs or metrics considered, as well as the overarching goals, advantages, and challenges associated with each application.

Table 7. Analysis of RPL OF-based IoT Applications

Technique Used	Application	OF	Metric	Goal	Advantage	Challenge
PA-RPL [75]	Smart Agriculture	Energy	Multiple	Enable sufficient partitioning in network data aggregation	Improved network connectivity	Low Energy efficiency and scalability
SCA-OF [59]		Energy	Radio Duty Cycle	Energy optimization of the A-LLN network	Prolongs network lifetime and improves QoS	Constrained memory and high computation complexity
PEERP [79]	Smart Healthcare	Energy	Multi-Hop	Priority-based health data classification	Energy efficient, High network lifetime, and throughput	High delay and packet loss
Evaluation of RPL OF in Healthcare [81]		OF0	ETX	Evaluating power consumption to improve PDR	High PDR	More complexity and High energy consumption
DYNASTI [83]	Smart city	No	Multiple metrics	Support of sporadic applications	Flexibility and Heterogeneity	High overhead and energy consumption
Hybrid RPL-Based protocol [84]		OF0	RSSI	To provide a sensing solution	Increases network lifetime and better QOS	Unpredictable coverage and mobility issues
Energy-aware RPL protocol [86]	Internet of Multimedia Things	Remaining Energy	Energy	To enhance network lifetime and balance multimedia traffic	Enhance network lifetime	High energy consumption and complexity
Free-BW RPL [87]		FreeBW-OF	Bandwidth	To optimize network bandwidth	Minimize congestion	Constrained QoS
UA-RPL [94]	Internet of Underwater Networks	Energy factor	Hop count and ETX	Splits the network traffic and improves RPL energy efficiency	Improve network lifetime	High energy in noisy environments and no reliability
HI-MOPD [93]		QoS	Multiple	Enable QoS-based initial storing node decision scheme.	Increase reliability and reduce route repair overhead.	Propagation of navigation issues in underwater networks.
Routing path selection approach [97]	Internet of Battlefield Environment	Energy	Latency	To formulate the data generation probabilities of tactical devices.	Reduces energy consumption and latency	Imbalanced energy usage and High latency

TA-RPL [102]	Industrial Internet of Things (IIoT)	Metric based	ETX	Handles heavy traffic using cross-layer approach	Efficient load balancing and improved bandwidth utilization	Imbalanced bandwidth problem
RAROF [103]		Energy	NVI	To enable the IIoT The system is more reliable and energy-efficient	Energy efficient, Extending Network	Unfair resource utilization
HRPL Protocol for 6LoWPAN [107]	Smart Home System	MRHOF	Energy and overhead	To improve RPL routing overhead by using the rebroadcast technique	Improve power consumption, network lifetime,	Constrained QoS
ARMOR [110]	Smart Mobility	Energy	TTR	Provide connection longevity and stability in the network	Improved reliability and power efficiency	Constraints to link stability, path predictability, and QoS
MARPL [111]		Energy	Neighborhood variability	To prevent unnecessary degradation of network performance	Short transmission range, low power consumption	Lack of mobility detection, packet loss, and frequent disconnections
OFQS [113]	Smart Grid	Energy	Latency	Provides differential QoS for various smart grid applications	Improved End-to-End delay, network lifetime, and PDR	No instance of support for effective traffic differentiation
Energy- and congestion-aware routing metric [112]		Energy and queue	Residual energy and queue status	Dynamically selects the parent node based on residue energy and queue status.	Improved average power consumption and PDR	They did not discuss the delay or latency.

5. Future Research Directions

As the diversity and complexity of IoT deployments grow, there arises a need for innovative approaches to enhance the performance and adaptability of RPL OFs across different application scenarios, which have unique requirements and challenges. This research direction includes investigating advanced algorithms, integration of emerging technologies such as machine learning and artificial intelligence, and customization of routing metrics to address specific application domains. Some of the future research directions are as follows.

- Smart Agriculture: Future research in smart farming agriculture could focus on developing OF that optimizes data aggregation and transmission processes. Furthermore, designing routing metrics to prioritize routes resilient to node failures and environmental disturbances for routing optimization. Inclusion of machine learning strategies to obtain dynamic network conditions to optimize the OFs dynamically.
- Smart Healthcare: Smart healthcare could further investigate OFs optimizing routing decisions for real-time health monitoring and telemedicine, ensuring

timely delivery of critical health data while minimizing latency. Design novel OFs with machine Q-learning solutions that can ensure QoS requirements by giving priority to the traffic according to its importance and healthcare urgency.

- Smart City: In smart city applications, future research could focus on addressing issues such as hot spots, thundering swarms, and bottlenecks originating from nodes one hop away from the sink, which would contribute to more efficient and resilient urban networks. Ensure that RPL-OFs can operate securely by preserving user privacy, especially in sensitive smart city applications.
- Internet of Multimedia Things (IoMT): Future research in the IoMT can focus on exploring the integration of edge computing capabilities into OFs for IoMT networks. This integration may reduce latency and bandwidth requirements while facilitating real-time multimedia analytics and decision-making.
- UIoT: In UIoT, the design of OFs that can seamlessly integrate underwater and surface networks has to be focused on enabling efficient data exchange between sensor nodes and surface-based IoT devices. The Future RPL-OFs will optimize the UIoT efficiency by including localization information and mobile node positions in their design.
- IIoT: In IIoT applications, the OF must prioritize QoS metrics such as latency, reliability, and bandwidth. This focus ensures the timely and reliable delivery of critical data within IIoT networks. Hence, factors such as node mobility, battery capacity, and energy harvesting capabilities should be considered during OF development to extend the lifespan of battery-operated devices and improve network sustainability.
- Smart Home: In smart home applications, user-centric routing approaches can be explored within OF for smart home networks. This process involves considering user preferences, behavior patterns, and device interactions to optimize routing decisions based on user-specific criteria such as device proximity, usage frequency, and application priorities.
- Smart Mobility: Machine learning or artificial intelligence techniques can be integrated into the routing protocol of Smart Mobility applications. Future work contributes to standardization efforts for accomplishing interoperability among distinct IoT applications by promoting wider adoption of optimized RPL-OFs.
- By focusing on these areas, RPL OFs can be tailored to meet the evolving demands of diverse IoT ecosystems, enabling more efficient, scalable, and resilient communication networks for a wide range of applications.

6. Conclusion

This survey has systematically reviewed the literature on RPL-OFs published between January 2015 and May 2024, analyzing 114 research works to provide an in-depth understanding of OF selection and its influence on routing performance across diverse IoT applications. It presented an overview of RPL, its standard OFs, enhanced metric formulations, and application-specific designs that collectively highlight the pivotal role of OFs in determining RPL's efficiency. This comprehensive survey revealed persistent challenges arising from limited metric consideration, reliance on single-metric designs, and suboptimal OF optimization. Particular emphasis was placed on addressing QoS-related concerns influenced by factors such as topology dynamics, traffic load, link quality, buffer management, and route optimization. This review also underscored how recent research efforts have advanced multi-metric and adaptive OFs to overcome the limitations of standard approaches and to better align with the heterogeneous requirements of IoT environments. By integrating the findings from existing studies, this survey shows that OF design must be tailored to application-specific requirements to guarantee robust, scalable, and efficient network performance. Moreover, this survey establishes a valuable foundation for future research on intelligent, adaptive, and security-aware OFs that can further enhance the reliability of RPL in next-generation IoT applications.

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