

# AN-RPL: Infrastructure-Assisted RPL Enhancement via Distributed Anchor Nodes for Mobile IoT Networks

Thang C. Vu<sup>1</sup>, Minh T. Nguyen<sup>2,\*</sup>, Mui D. Nguyen<sup>2</sup>, Long Q. Dinh<sup>1</sup>, Dung T. Nguyen<sup>1</sup>, and Duc M. Ngo<sup>2</sup>

<sup>1</sup> Thai Nguyen University of Information and Communication Technology, Thai Nguyen University, Thai Nguyen 240000, Viet Nam; e-mail: vcthang@ictu.edu.vn, dqlong@ictu.edu.vn, ntdungcndt@ictu.edu.vn

<sup>2</sup> Thai Nguyen University of Technology, Thai Nguyen University, Thai Nguyen 240000, Viet Nam; e-mail: nguyentuanminh@tnut.edu.vn, ducmui@tnut.edu.vn, ngoduc198-tdh@tnut.edu.vn

\* Corresponding Author : Minh T. Nguyen 

**Abstract:** The Internet of Things (IoT) has attracted significant attention from the research community due to its wide range of applications. However, the limited energy, processing capability, storage, and communication capacity of IoT devices require routing solutions that are both lightweight and efficient. To address these constraints, the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) was introduced in 2012 as a routing protocol specifically designed for resource-constrained IoT environments. Although RPL performs reliably in static deployments, its performance degrades considerably in mobile environments because of frequent topology changes, slow Trickle timer convergence, and excessive parent churn. This paper proposes Anchor-Node RPL (AN-RPL), an infrastructure-assisted enhancement of RPL that strategically deploys distributed fixed anchor nodes as stable DODAG roots while requiring only minimal firmware modification on mobile sensor nodes, namely a single anchor-flag check during parent selection. Simulation experiments conducted in Cooja using both OF0 and MRHOF objective functions across four scenarios (static, mobile with one, two, and four anchor nodes) demonstrate that AN-RPL with four anchor nodes improves the Data Delivery Ratio (DDR) by up to 30.6 percentage points, reduces the average hop count by up to 51.2%, lowers parent churn by up to 89.5%, and decreases average energy consumption by up to 14.8% compared with conventional single-root mobile RPL. These results demonstrate that infrastructure-assisted anchor deployment provides an effective and practical approach for improving routing reliability and efficiency in mobile RPL-based IoT networks.

**Keywords:** Anchor Node Deployment; Internet of Things (IoT); IPv6 Routing; Low-Power and Lossy Networks (LLNs); Mobility-Aware Routing; Mobile IoT; Routing Protocol for Low-Power and Lossy Networks (RPL); Wireless Sensor Networks (WSNs).

Received: May, 11<sup>th</sup> 2026

Revised: June, 18<sup>th</sup> 2026

Accepted: June, 19<sup>th</sup> 2026

Published: June, 30<sup>th</sup> 2026



**Copyright:** © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) licenses (<https://creativecommons.org/licenses/by/4.0/>)

## 1. Introduction

The Internet of Things (IoT) has emerged as a key paradigm for connecting billions of resource-constrained devices across diverse application domains, including smart cities, smart agriculture, smart transportation, and smart grids [1], [2]. Many of these applications rely on IEEE 802.15.4, a low-power and low-data-rate wireless communication standard that enables energy-efficient networking for constrained devices. Networks built upon IEEE 802.15.4 are commonly categorized as Low-Power and Lossy Networks (LLNs), where nodes operate under strict limitations in energy, processing capability, memory, and communication bandwidth [3]. These resource constraints require routing protocols specifically designed for reliable and efficient communication under constrained operating conditions. To address these challenges, the Internet Engineering Task Force (IETF) Routing Over Low-Power and Lossy Networks (ROLL) Working Group standardized the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) through RFC 6550 in 2012 [3]. RPL constructs a Destination-Oriented Directed Acyclic Graph (DODAG) rooted at a sink node and supports upward, downward, and peer-to-peer communication. Its routing maintenance is coordinated by the

Trickle algorithm (RFC 6206), which dynamically balances routing responsiveness and control overhead by adapting the dissemination frequency of DODAG Information Object (DIO) messages [3].

Although RPL has proven effective in static LLN deployments, the rapid growth of mobile IoT applications has exposed several fundamental limitations of its original design. Applications involving connected vehicles, wearable devices, unmanned platforms, livestock monitoring, and mobile environmental sensing require routing protocols capable of maintaining reliable communication despite continuous topology changes [4]–[6]. However, the standard RPL architecture was not originally designed to cope with persistent node mobility. As nodes move, routing paths are frequently disrupted, leading to packet loss and temporary disconnections. Meanwhile, the conservative behavior of the Trickle algorithm delays routing adaptation in rapidly changing topologies, prolonging routing instability. Frequent topology changes also increase parent churn, forcing mobile nodes to repeatedly search for new parents, which degrades packet delivery performance while increasing retransmissions and energy consumption. These challenges are further exacerbated by the conventional single-root DODAG architecture, where nodes located farther from the sink experience longer routing paths and become more vulnerable to connectivity degradation. Recent surveys consistently identify these interconnected limitations as the primary factors restricting the applicability of conventional RPL in highly dynamic mobile environments [7], [8].

To address these limitations, several mobility-aware RPL enhancements have been proposed, including Corona-based RPL (Co-RPL) [9], Mobility Enhanced RPL (ME-RPL) [10], Energy and Mobility Aware RPL (EMA-RPL) [11], Mobility Prediction RPL (MP-RPL) [12], Q-learning-based Fast Switching RPL (QFS-RPL) [13], Mobility Support Extension RPL (MSE-RPL) [14], and Robust Mobility RPL (RM-RPL) [15]. These approaches improve routing decisions through mobility-aware metrics, RSSI-based prediction, speed classification, or adaptive learning mechanisms. However, these improvements are generally achieved by increasing protocol complexity through additional routing metrics, memory structures, or decision modules that require firmware modifications on mobile sensor nodes. Consequently, the computational overhead, memory usage, and implementation complexity increase, limiting their suitability for highly resource-constrained IoT devices. Furthermore, most existing studies primarily optimize routing decisions without addressing the structural limitation imposed by the conventional single-root DODAG architecture.

Motivated by these observations, this paper proposes Anchor-Node RPL (AN-RPL), an infrastructure-assisted enhancement that addresses mobility from the network architecture rather than by increasing protocol complexity. Instead of introducing sophisticated routing intelligence into mobile nodes, AN-RPL strategically deploys a small number of fixed anchor nodes that operate as distributed DODAG roots throughout the deployment area. Mobile nodes require only a minimal firmware modification consisting of a single anchor-flag check during parent selection, thereby preserving the lightweight characteristics of standard RPL while improving routing robustness under mobility. The central hypothesis of this study is that strategically deploying a limited number of anchor nodes as distributed DODAG roots can improve routing performance in mobile RPL networks by shortening the average topological distance to stable routing infrastructure, increasing connectivity availability, and reducing parent churn through the Root-First Preference Principle. Consequently, higher routing reliability and lower communication overhead are expected without substantially increasing protocol complexity. The main contributions of this work are summarized as follows:

- An infrastructure-assisted RPL enhancement, namely Anchor-Node RPL (AN-RPL), is proposed to improve routing performance in mobile IoT environments through strategically distributed anchor nodes while requiring only minimal modifications to mobile sensor nodes.
- A theoretical rationale and routing framework are established to explain how distributed anchor deployment and the Root-First Preference Principle improve route stability by reducing topological distance, mitigating parent churn, and increasing connectivity robustness.
- A comprehensive simulation-based evaluation is conducted in Cooja using both OF0 and MRHOF objective functions under static and multiple mobile deployment scenarios, demonstrating consistent improvements in data delivery ratio, hop count, parent churn, and energy consumption.

The remainder of this paper is organized as follows. Section 2 reviews representative RPL enhancements for mobile environments. Section 3 presents the system model, problem formulation, and AN-RPL design principles. Section 4 describes the simulation setup and experimental evaluation. Section 5 discusses the practical implications and limitations of the proposed approach. Finally, Section 6 concludes the paper and outlines future research directions.

## 2. Related Work

Low-Power and Lossy Networks (LLNs) constitute the communication backbone of many Internet of Things (IoT) applications, where resource-constrained devices require routing protocols that are both reliable and energy efficient [1], [2]. To address these requirements, the Internet Engineering Task Force (IETF) standardized the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) through RFC 6550 in 2012. RPL constructs a Destination-Oriented Directed Acyclic Graph (DODAG) rooted at a sink node and supports upward, downward, and peer-to-peer communication, while the Trickle algorithm adaptively regulates routing control messages to balance routing responsiveness and communication overhead [3], [16]. Comprehensive reviews of IoT networking protocols and communication mechanisms are available in [17]–[20].

Although RPL performs effectively in static deployments, previous studies have reported several limitations in large-scale and mobile environments, including excessive control overhead, slow routing convergence, security concerns, and degraded routing performance under node mobility [9]–[15], [21], [22]. Consequently, numerous RPL enhancements have been proposed to improve mobility support. Table 1 summarizes the representative mobile-RPL approaches discussed in this section and compares their main characteristics.

**Table 1.** Comparison of representative mobile-RPL enhancement approaches.

Criterion	Co-RPL	ME-RPL	EMA-RPL	MP-RPL	QFS-RPL	MSE-RPL	RM-RPL	AN-RPL (Proposed)
Firmware modification required on mobile nodes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes (minimal)
Computational overhead	High	Medium	High	Medium	High	Medium	High	Very Low
Memory overhead	High	Low	High	High	Very High	Medium	High	Very Low
Infrastructure-assisted operation	No	No	No	No	No	No	No	Yes
Deployment complexity	High	Medium	High	High	High	Medium	High	Low
Validated mobility level	Moderate	Moderate	Moderate	Variable	High	Moderate	High	Moderate
RFC 6550 compatibility	Partial	Partial	Partial	Partial	Partial	Partial	Partial	Mostly compatible

Co-RPL organizes the network into concentric corona regions surrounding the root node, enabling parent selection to exploit location-aware information and improve routing under node mobility [9]. By updating zone membership as nodes move, Co-RPL achieves more stable parent selection in moderately dynamic environments. However, its dependence on predefined geographic regions and a conventional single-root architecture limits scalability in large or irregular deployment areas, where node mobility is less predictable.

ME-RPL improves route adaptation by introducing mobility flags into DIO messages, allowing nodes to distinguish between static and mobile neighbors during parent selection [10]. Combined with a more aggressive Trickle timer reset strategy, this approach accelerates topology convergence after mobility events. Nevertheless, the increased frequency of Trickle resets may generate considerable control overhead in dense or highly dynamic networks, while the mobility flag mechanism requires firmware modifications on mobile sensor nodes.

EMA-RPL addresses mobility by predicting potential link failures from Received Signal Strength Indicator (RSSI) variations and initiating proactive handovers before communication is interrupted [11]. This mechanism effectively reduces packet loss caused by broken links but relies on RSSI history buffers and trajectory estimation algorithms, increasing both memory consumption and computational requirements on resource-constrained devices.

MP-RPL enhances parent selection through a Speed Node Status Classifier (SNSC) that estimates node mobility from variations in link quality and prioritizes relatively stable nodes as routing parents [12]. Although this strategy improves routing stability across heterogeneous mobility scenarios, its effectiveness depends on accurate mobility estimation and introduces additional model parameters and memory requirements that may not be suitable for ultra-low-power platforms.

QFS-RPL integrates Q-learning-based multipath routing with an inverse Trickle mechanism to accelerate parent recovery after route failures in mobile environments [13]. The combination improves packet delivery performance by enabling faster routing adaptation. However, the learning-based framework increases implementation complexity and still requires firmware modifications on mobile sensor nodes.

MSE-RPL extends conventional RPL by introducing mobility support mechanisms that maintain seamless connectivity for all network nodes except the root node [14]. The protocol effectively mitigates communication disruptions caused by mobility and physical obstacles in dynamic environments. However, these enhancements require additional firmware modifications, increasing implementation complexity on constrained devices.

RM-RPL introduces a new objective function together with loop-prevention and critical-packet handling mechanisms to improve routing performance in highly dynamic and dense mobile IoT networks [15]. Although the protocol demonstrates strong mobility support, these additional routing functions also require substantial firmware modifications and increase the overall complexity of mobile sensor nodes.

Despite their different design philosophies, existing mobile-RPL enhancements share several common characteristics. Most approaches improve routing performance by embedding additional routing intelligence within mobile sensor nodes through mobility prediction, RSSI history, classifiers, or learning mechanisms. While these techniques enhance route adaptation under mobility, they inevitably increase computational complexity, memory consumption, firmware modification requirements, and deployment overhead, making their adoption less attractive for highly resource-constrained IoT devices. Moreover, they continue to operate within the conventional single-root DODAG architecture, leaving one of the fundamental structural limitations of RPL largely unresolved. These observations suggest that improving mobile RPL performance does not necessarily require increasingly sophisticated routing algorithms on mobile nodes. Instead, an infrastructure-assisted design that strengthens routing stability through strategically deployed anchor nodes offers an alternative direction while preserving the lightweight characteristics and compatibility of standard RPL.

### 3. The Proposed Method: Anchor-Node RPL

This section presents the system model, problem formulation, design principles, routing decision process, and protocol overhead analysis of the proposed Anchor-Node RPL (AN-RPL).

#### 3.1. System Model and Problem Formulation

A mobile IoT network is deployed over an area  $A$  of size  $L \times W$  m<sup>2</sup>. The set of mobile sensor nodes is denoted by  $M = \{m_1, m_2, \dots, m_k\}$ , while the set of anchor nodes is represented by  $R = \{r_1, r_2, \dots, r_k\}$ , where  $n \gg k$ . Each mobile node  $m_i \in M$  follows the Random Waypoint Mobility Model [23], selecting random destinations within the deployment area and moving at speeds uniformly distributed in the range  $[V_{min}, V_{max}]$ , followed by a randomly selected pause time. In contrast, each anchor node  $r_j \in R$  remains stationary at a predefined location and operates as an independent DODAG root within the standard RPL framework. All anchor nodes are connected to a centralized data sink or the Internet through a reliable backbone infrastructure, such as wired Ethernet or a dedicated wireless backhaul.

One of the primary challenges in mobile IoT networks is the continuous evolution of network topology caused by node mobility. Unlike conventional RPL deployments, where a single root maintains a relatively stable DODAG, mobile nodes frequently move away from their preferred parents, resulting in repeated parent changes, increased routing instability, higher control overhead, packet loss, and additional energy consumption associated with route reconstruction.

AN-RPL addresses this limitation by strategically deploying multiple fixed anchor nodes throughout the network. Instead of relying on a single DODAG root, distributed anchor

nodes reduce the average routing distance between mobile nodes and stable routing infrastructure while extending network coverage. Consequently, mobile nodes are less likely to experience prolonged disconnections or repeated route reconstruction as they move across the deployment area.

The underlying rationale of AN-RPL can be interpreted from a geometric coverage perspective. Assuming that  $k$  anchor nodes are approximately uniformly distributed over an  $L \times W$  m<sup>2</sup> deployment area, the expected distance between a randomly located mobile node and its nearest anchor decreases approximately in proportion to  $\frac{1}{\sqrt{k}}$ . As a consequence, the average hop distance to the nearest DODAG root is also reduced. Given a transmission range of  $r$ , increasing the number of anchor nodes enlarges the effective coverage region, thereby increasing the probability that a mobile node remains within the communication range of at least one anchor node.

Improved spatial coverage directly contributes to higher routing stability. Since anchor nodes remain stationary, communication links between mobile nodes and nearby anchors generally exhibit more stable link quality than links established solely between mobile nodes. Consequently, routing metrics such as the Expected Transmission Count (ETX) used by MRHOF are expected to produce more stable parent selections, thereby reducing parent churn while improving packet delivery performance and communication efficiency.

### 3.2. AN-RPL Design Principles

AN-RPL introduces a set of  $k$  fixed anchor nodes that operate as geographically distributed DODAG roots. Each anchor independently constructs and maintains its own DODAG while periodically broadcasting DIO messages according to the standard Trickle algorithm. Mobile nodes receive DIO messages from nearby anchors and associate with the parent offering the lowest routing cost under the selected RPL objective function. Figure 1 illustrates the overall AN-RPL architecture, where five mobile nodes (MN1–MN5) are associated with their nearest anchor nodes. The figure also illustrates the handover process that occurs when a mobile node (MN5) moves from one anchor coverage region to another.

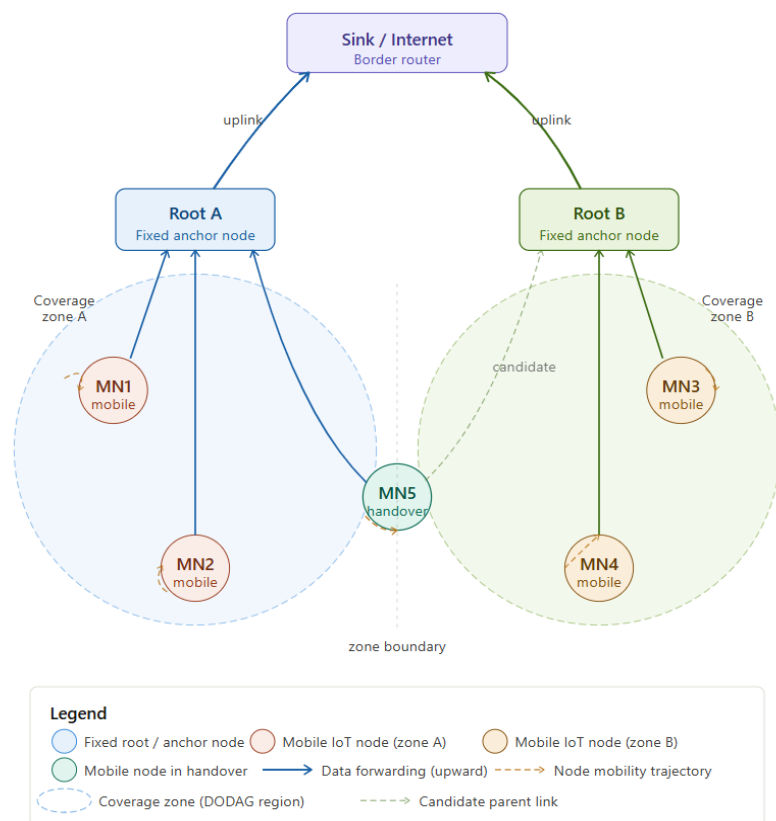


Figure 1. Architecture of the proposed AN-RPL with distributed anchor nodes and inter-anchor handover.

The AN-RPL architecture is governed by the following design principles.

- RFC 6550 Core Compatibility: AN-RPL preserves the core routing mechanisms defined in RFC 6550 for both anchor and mobile nodes. Only a minimal firmware modification is introduced on mobile sensor nodes through the addition of a single-bit anchor flag within the DIO option field, enabling implementation of the proposed Root-First Preference Principle without altering the fundamental RPL protocol operation.
- No Inter-Anchor Coordination: Each anchor node independently operates as a DODAG root without exchanging routing information or coordinating DODAG boundaries with neighboring anchors. Parent selection remains entirely decentralized, allowing each mobile node to independently select its preferred anchor based solely on locally received DIO messages. This design avoids additional synchronization overhead while preserving protocol simplicity.
- Root-First Preference Principle: When a mobile node  $m_i$  simultaneously receives DIO messages from both an anchor node  $r_j \in R$  and a neighboring mobile node  $m_j \in M$  with comparable routing costs, preference is given to the anchor node during parent selection. This simple tie-breaking mechanism intentionally biases routing toward the more stable infrastructure, thereby reducing unnecessary parent changes and improving routing stability under node mobility.

### 3.3. Routing Decision Process

In AN-RPL, each mobile node  $m_i$  maintains a candidate parent set  $P_i$  containing all neighboring nodes from which valid DIO messages have been received during the current Trickle interval. A neighboring node  $p$  is considered a valid parent candidate only if (i) its advertised DODAG rank,  $Rank(p)$ , is strictly lower than  $Rank(m_i)$ , thereby preserving loop freedom, and (ii) it belongs to the same DODAG instance as  $m_i$ . Among all valid candidates, the preferred parent is selected as the node that minimizes the routing cost defined by the active RPL objective function,  $OF(\cdot)$ . Figure 2 illustrates the routing decision workflow implemented in AN-RPL, including the candidate-parent evaluation process and the Root-First Preference Principle used during parent selection.

Under Objective Function Zero (OF0) [24], routing decisions are based solely on hop count, where the preferred parent is the neighbor with the lowest DODAG rank, corresponding to the shortest path toward the root node. In contrast, the Minimum Rank with Hysteresis Objective Function (MRHOF) [25] computes routing cost from the cumulative Expected Transmission Count (ETX) along the path to the root, enabling link-quality-aware routing. To improve routing stability, MRHOF employs a hysteresis threshold  $\Delta ETX$ , allowing parent changes only when the improvement in path quality exceeds the predefined threshold. This mechanism suppresses unnecessary parent switching caused by transient link-quality fluctuations during node mobility.

The distinguishing routing mechanism of AN-RPL is the Root-First Preference Principle. When a mobile node  $m_i$  simultaneously receives valid DIO messages from both an anchor node  $r_j \in R$  and a neighboring mobile node  $m_j \in M$ , and the corresponding routing costs are equal or sufficiently similar under the active objective function, preference is given to the anchor node during parent selection. This tie-breaking strategy intentionally biases routing toward stable infrastructure rather than mobile intermediate nodes, thereby reducing parent churn and improving routing stability under dynamic network conditions.

### 3.4. Anchor Node Overhead Analysis

Although AN-RPL improves routing performance through infrastructure-assisted deployment, the introduction of anchor nodes also incurs additional overhead. This overhead can be analyzed from three complementary perspectives.

- Communication overhead: Each anchor node independently executes the standard Trickle algorithm and periodically broadcasts DIO messages. Consequently, the aggregate DIO transmission rate increases approximately in proportion to the number of deployed anchor nodes ( $k$ ) relative to the conventional single-root architecture. However, because mobile nodes are generally located closer to at least one anchor node, DAO

advertisements traverse fewer hops before reaching the destination, partially compensating for the increase in DIO traffic. In the largest deployment considered in this study ( $k=4$ ), the increase in control traffic is bounded by four anchor nodes, while the routing overhead experienced by mobile nodes is reduced through fewer parent discovery and route recovery operations.

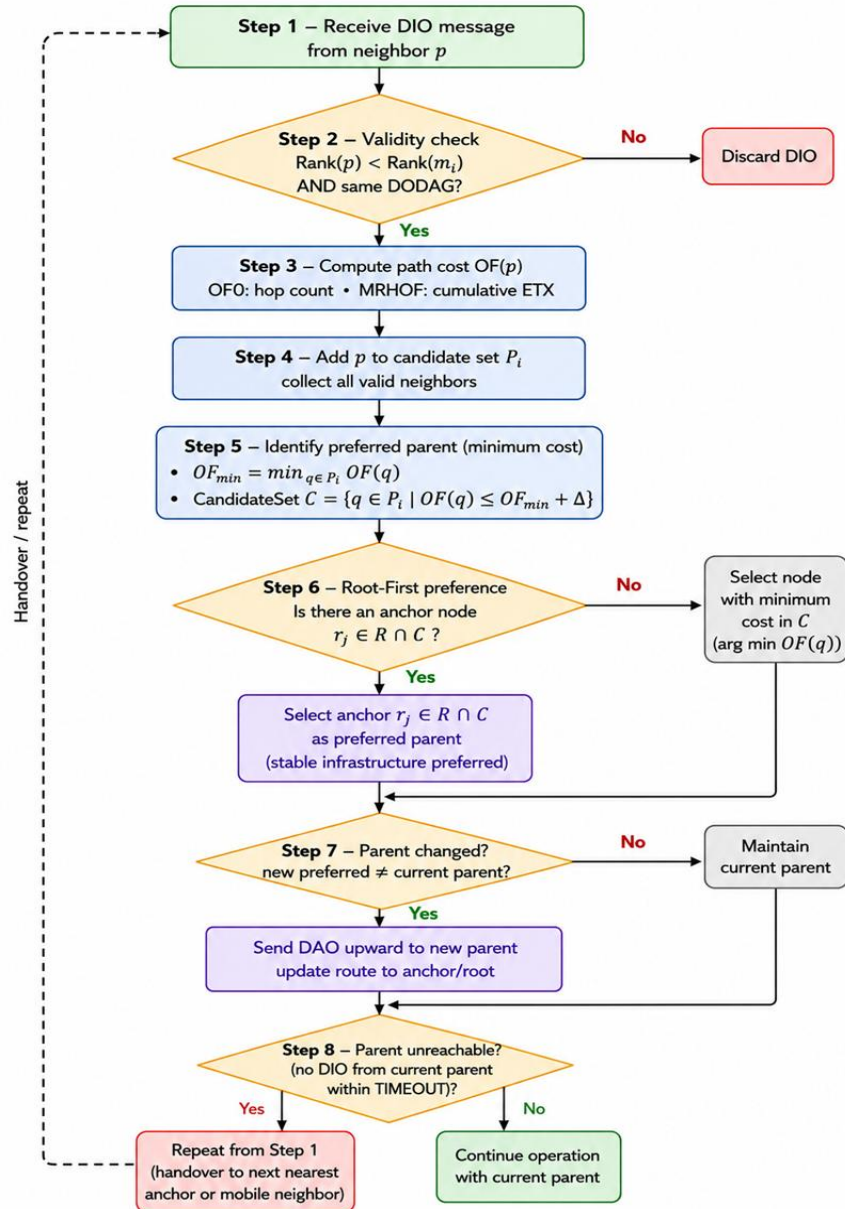


Figure 2. Flowchart of the proposed AN-RPL routing process incorporating the Root-First Preference Principle.

- Memory overhead: AN-RPL introduces only minimal additional memory requirements on mobile sensor nodes. The required storage is limited to a single anchor-identification flag together with a small amount of parent-selection information, making the proposed enhancement suitable for resource-constrained LLN devices.
- Deployment overhead: The deployment of anchor nodes introduces an additional one-time infrastructure cost. However, for the  $100\text{ m} \times 100\text{ m}$  deployment scenario considered in this study, four anchor nodes provide broad network coverage while substantially improving routing stability. The resulting trade-off between infrastructure cost and routing performance is quantitatively evaluated in Section 4.

## 4. Simulation Results and Performance Analysis

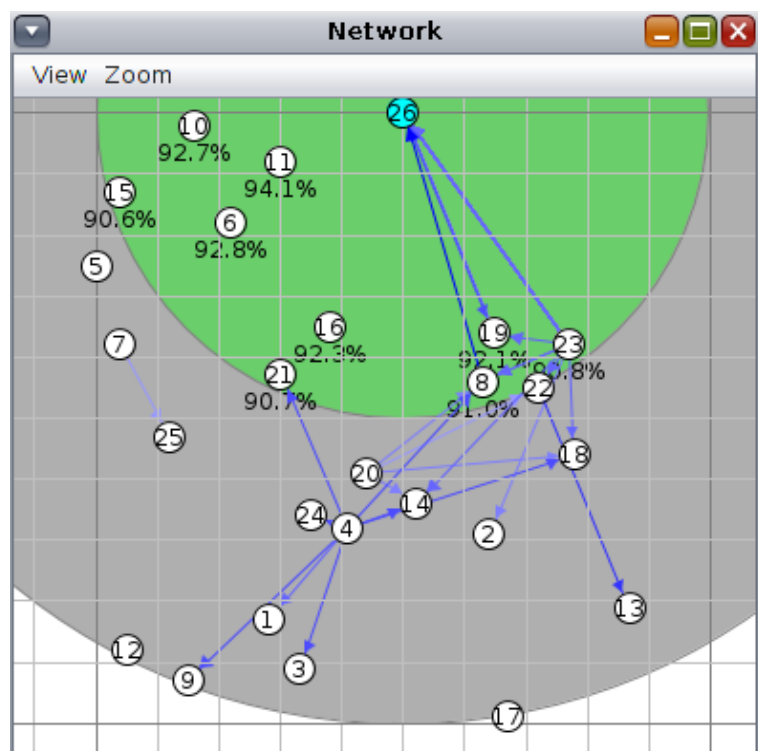
This section presents the simulation methodology, network configuration, experimental scenarios, performance evaluation, and the trade-off analysis of the proposed AN-RPL approach.

### 4.1. Simulation Setup and Network Configuration

All simulations were conducted using the Cooja simulator running on Contiki 3.0 under Ubuntu 14.04 LTS. Node mobility traces were generated with BonnMotion v3.0.1 using the Random Waypoint mobility model. AN-RPL was implemented by modifying the RPL objective function module in Contiki 3.0. Specifically, the candidate-parent table was extended with a single Boolean variable (*is\_anchor*), and the parent-selection procedure was modified to implement the proposed Root-First Preference Principle. No changes were made to the core RPL protocol, including the DIO/DAO message formats, Trickle algorithm, or other routing components. To evaluate the impact of anchor-node deployment on routing performance, four representative network scenarios were considered.

- Scenario 1 (S1 – Baseline Static): Twenty-five static sensor nodes connected to a single DODAG root. This scenario serves as the upper-bound performance reference for conventional static RPL.
- Scenario 2 (S2 – Mobile, One Anchor): Twenty-five mobile sensor nodes connected to a single fixed DODAG root, as illustrated in Figure 3. This scenario represents the baseline performance of standard mobile RPL.
- Scenario 3 (S3 – Mobile, Two Anchors): Twenty-five mobile sensor nodes supported by two strategically deployed fixed anchor nodes acting as distributed DODAG roots.
- Scenario 4 (S4 – Mobile, Four Anchors): Twenty-five mobile sensor nodes supported by four strategically deployed anchor nodes, as illustrated in Figure 4.

All mobile nodes were randomly deployed within a  $100\text{ m} \times 100\text{ m}$  network area. Node mobility followed the Random Waypoint model generated by BonnMotion, with a minimum speed of 1 m/s, a maximum speed of 2 m/s, and a pause time uniformly distributed between 0 and 30 s. These settings represent moderate pedestrian mobility commonly encountered in indoor, campus, and smart-building IoT environments.



**Figure 3.** Simulation scenario consisting of 25 mobile nodes and one DODAG root (Node 26).

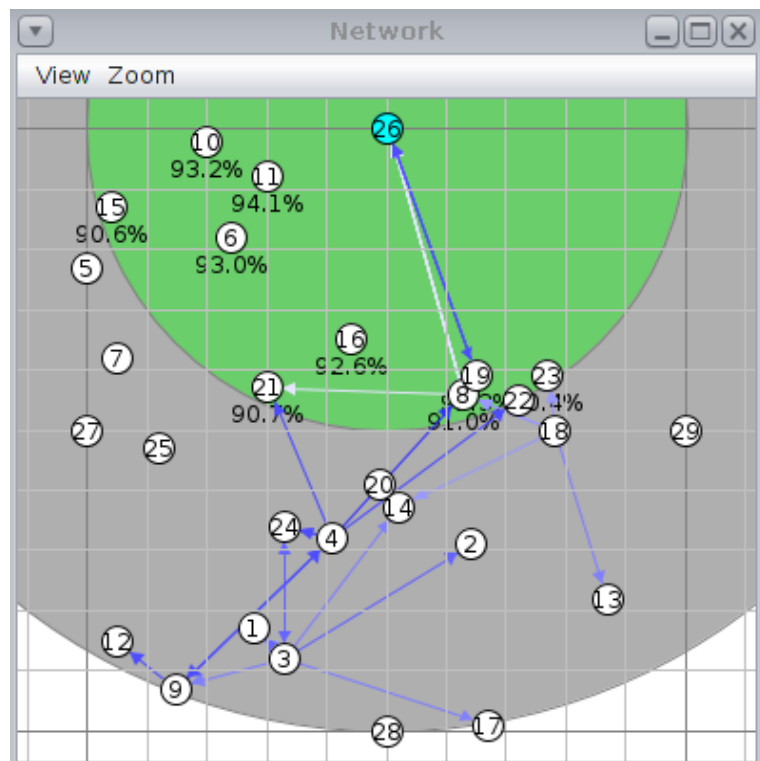


Figure 4. Simulation scenario consisting of 25 mobile nodes and four distributed anchor nodes (Nodes 26–29).

The main simulation parameters are summarized in Table 2.

Table 2. Simulation parameters

Parameter	Value
Simulation platform	Cooja (Contiki 3.0)
Wireless communication model	Unit Disk with Interference (UDI)
Number of mobile (leaf) nodes	25
Network area	100 m × 100 m
Transmission range	50 m
Interference range	100 m
Mobility model	Random Waypoint (BonnMotion v3.0.1)
Node speed	Uniform distribution [1, 2] m/s
Pause time	Uniform distribution [0, 30] s
Data packet interval	60 s (random offset)
MAC protocol	CSMA/ContikiMAC
RPL objective functions	OF0 (Hop Count), MRHOF (ETX)
Simulation duration	1800 s

#### 4.2. Performance Evaluation Metrics

The proposed AN-RPL is designed to improve routing reliability and stability in mobile IoT environments through infrastructure-assisted anchor deployment while maintaining low protocol overhead. Accordingly, four complementary metrics are selected to evaluate the proposed approach from the perspectives of communication reliability, routing stability, routing efficiency, and energy efficiency.

Data Delivery Ratio (DDR) represents the percentage of application data packets successfully received at any anchor node relative to the total number of packets transmitted by all mobile nodes. This metric serves as the primary indicator of communication reliability and

evaluates the ability of AN-RPL to maintain successful packet delivery under node mobility. DDR is computed as:

$$DDR(\%) = \frac{N_{received}}{N_{sent}} \times 100 \quad (1)$$

where  $N_{received}$  denotes the total number of successfully received data packets and  $N_{sent}$  represents the total number of transmitted data packets.

Average Parent Changes (Parent Churn) is defined as the average number of preferred-parent changes experienced by each mobile node during the simulation period. A lower churn value indicates more stable routing paths, fewer route recovery operations, and reduced control overhead. This metric directly reflects the effectiveness of the proposed Root-First Preference Principle in stabilizing parent selection. It is calculated as:

$$PC = \frac{1}{N} \sum_{i=1}^N C_i \quad (2)$$

where  $C_i$  is the number of parent changes recorded by node  $i$ , and  $N$  is the total number of mobile nodes.

Average energy consumption measures the average energy expended by each node during the simulation, expressed in millijoules (mJ), using the Contiki PowerTrace energy estimation model. The reported value includes the energy consumed during packet transmission, reception, idle listening, and processing. Lower energy consumption indicates that improved routing stability reduces unnecessary retransmissions, control traffic, and route maintenance operations. The average energy consumption is given by:

$$E_{avg} = \frac{1}{N} \sum_{i=1}^N E_i \quad (3)$$

where  $E_i$  denotes the total energy consumed by node  $i$ .

Average hop count represents the average number of forwarding hops required for a data packet to reach its destination. Since AN-RPL strategically deploys distributed anchor nodes, this metric evaluates whether the proposed architecture successfully shortens routing paths compared with the conventional single-root RPL architecture. A lower hop count generally indicates more efficient routing with reduced communication delay and transmission cost. The metric is computed as

$$H_{avg} = \frac{1}{N_p} \sum_{j=1}^{N_p} H_j \quad (4)$$

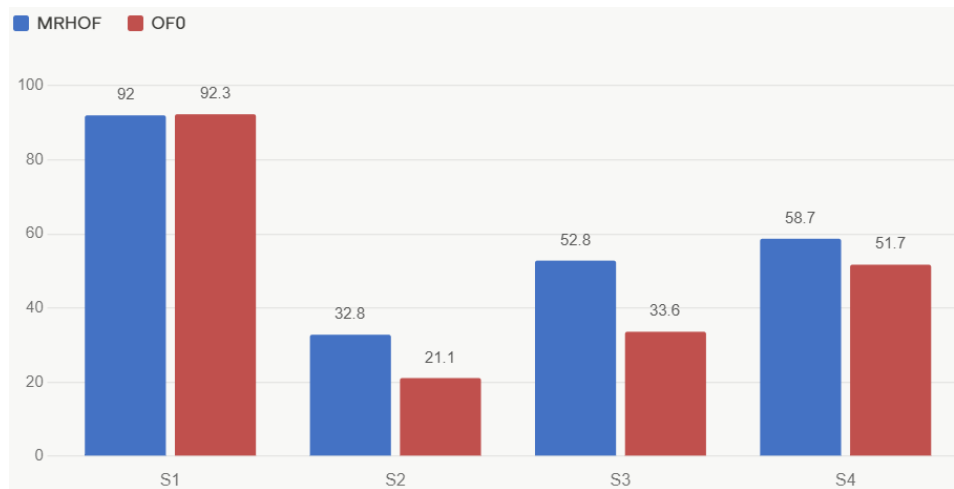
where  $H_j$  denotes the hop count of packet  $j$ , and  $N_p$  is the total number of successfully delivered packets.

### 4.3. Simulation Results

The experimental results are presented according to the four performance metrics introduced in Section 4.2. The following analysis examines how increasing the number of distributed anchor nodes influences communication reliability, routing stability, energy efficiency, and routing efficiency under the OF0 and MRHOF objective functions. Particular attention is given to the relationship between anchor-node density and the resulting routing performance, thereby providing empirical validation of the proposed AN-RPL design. Communication reliability is first evaluated using the DDR, which measures the ability of the network to successfully deliver application packets under node mobility. Figure 5 presents the DDR obtained under the four evaluated scenarios using the OF0 and MRHOF objective functions.

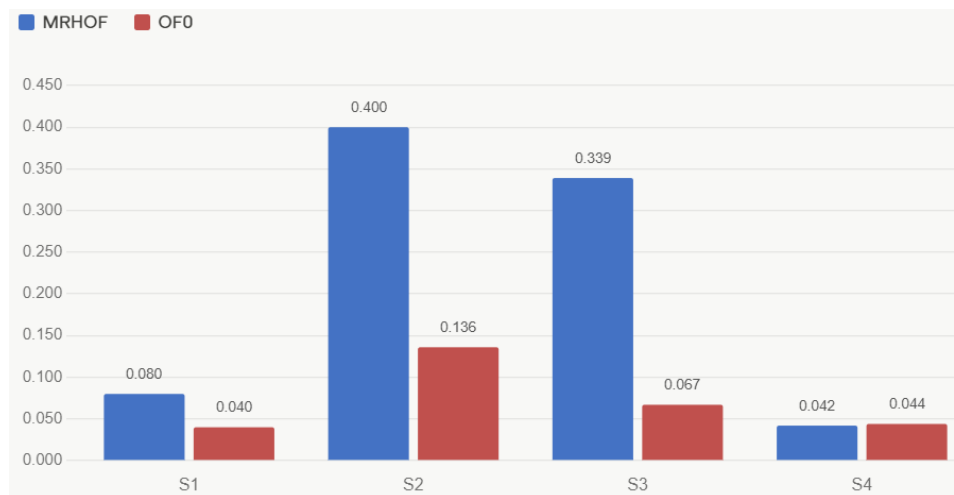
Under the static baseline (S1), both objective functions achieve comparable DDR values of approximately 92.3%, confirming that conventional RPL performs reliably when network topology remains stable. Once node mobility is introduced (S2), DDR decreases substantially to approximately 21.1% under OF0 and 32.8% under MRHOF because frequent topology changes interrupt routing paths and increase packet loss. The consistently higher DDR achieved by MRHOF indicates that ETX-based parent selection is more effective than hop-

count-based routing in maintaining reliable communication under dynamic network conditions.



**Figure 5.** DDR across the four evaluated scenarios under OF0 and MRHOF objective functions.

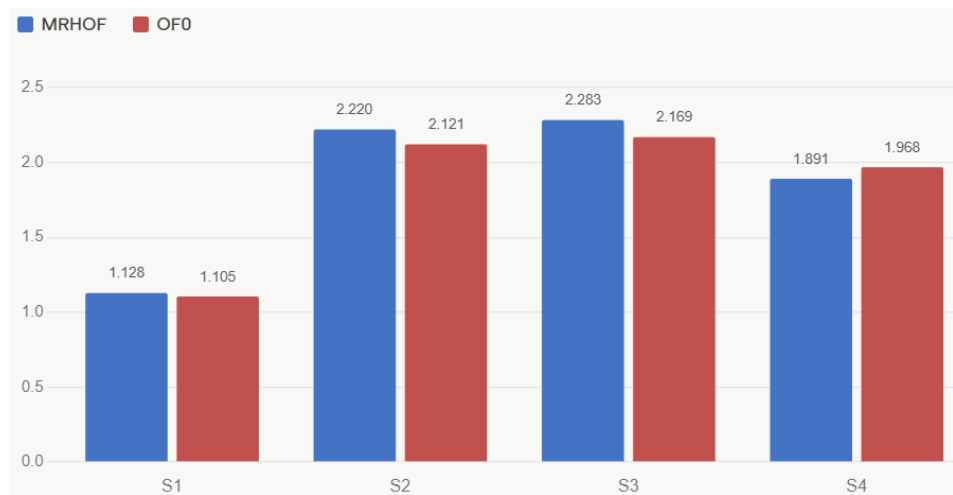
Increasing the number of anchor nodes progressively improves packet delivery performance. With two anchor nodes (S3), DDR increases to approximately 33.6% under OF0 and 52.8% under MRHOF. Deploying four anchor nodes (S4) further increases DDR to approximately 51.7% and 58.7%, corresponding to improvements of 30.6 and 25.9 percentage points, respectively, compared with the single-anchor mobile baseline. These results indicate that distributed anchor deployment effectively reduces routing disruptions by maintaining shorter and more stable paths to the network infrastructure, supporting the hypothesis that increasing anchor availability mitigates temporary connectivity loss caused by node mobility. The observed improvement in DDR further suggests that routing becomes more stable as additional anchor nodes are deployed. This hypothesis is examined by analyzing the frequency of parent changes, as presented in Figure 6.



**Figure 6.** Average parent changes per mobile node across the four evaluated scenarios under OF0 and MRHOF objective functions.

Both objective functions exhibit very low parent churn in the static scenario (approximately 0.04 for OF0 and 0.08 for MRHOF), indicating that parent reselection rarely occurs when network topology remains unchanged. Introducing node mobility (S2) significantly increases parent churn, reaching approximately 0.136 under OF0 and 0.400 under MRHOF. Frequent topology changes repeatedly invalidate preferred parent relationships, forcing mobile nodes to perform additional parent discovery and route reconstruction.

As additional anchor nodes are deployed, parent churn decreases consistently for both objective functions. With four anchor nodes, parent churn is reduced to approximately 0.044 under OF0 and 0.042 under MRHOF, representing reductions of approximately 67.6% and 89.5%, respectively, relative to the single-anchor mobile scenario. This substantial reduction demonstrates the effectiveness of the proposed Root-First Preference Principle in maintaining stable parent associations. By preferentially selecting nearby anchor nodes when routing costs are comparable, unnecessary parent switching is significantly reduced despite continuous node mobility. Since frequent parent changes incur additional control-message exchanges, route recovery operations, and retransmissions, improved routing stability is expected to reduce the overall energy consumption of the network. This relationship is examined in Figure 7, which illustrates the average energy consumption per node across all evaluated scenarios.



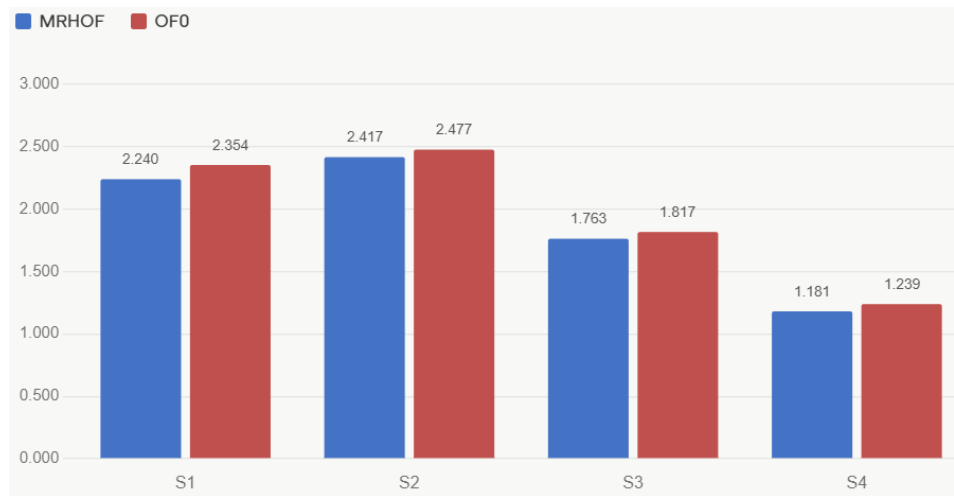
**Figure 7.** Average energy consumption per node (mJ) across the four evaluated scenarios.

Under the static scenario, OF0 consumes slightly less energy than MRHOF (approximately 1.105 mJ versus 1.128 mJ per node), mainly because OF0 performs simpler routing decisions without continuous ETX evaluation. Once mobility is introduced, energy consumption increases for both objective functions as frequent route failures trigger additional retransmissions, parent discovery, and control-message exchanges. The increase is more pronounced under MRHOF because continuous link-quality estimation introduces additional processing overhead despite improving routing reliability.

Deploying additional anchor nodes gradually reduces energy consumption under both objective functions. With four anchor nodes, MRHOF achieves the lowest average energy consumption (approximately 1.891 mJ per node), corresponding to reductions of 10.8% relative to the OF0 single-anchor baseline and 14.8% relative to the MRHOF single-anchor configuration. The observed reduction closely follows the decrease in parent churn, indicating that more stable routing substantially reduces route maintenance operations, retransmissions, and radio activity. These findings suggest that the infrastructure cost introduced by additional anchor nodes is partially compensated by improved communication efficiency.

Besides improving routing stability, deploying additional anchor nodes is also expected to shorten the routing distance between mobile nodes and the nearest DODAG root. This effect is evaluated through the average hop count, as presented in Figure 8. Under the static scenario, OF0 and MRHOF achieve average hop counts of approximately 2.354 and 2.240 hops, respectively. Introducing mobility slightly increases hop count because mobile nodes cannot always maintain connections with the most efficient routing parents. Consequently, OF0 exhibits a slightly higher hop count (approximately 2.477) than MRHOF (approximately 2.419), reflecting the benefit of ETX-aware routing under dynamic conditions. As the number of anchor nodes increases, the average hop count decreases substantially. With four anchor nodes, the average hop count is reduced to approximately 1.239 hops under OF0 and 1.181 hops under MRHOF, representing reductions of 49.98% and 51.2%, respectively, compared with the single-anchor mobile baseline. These results directly validate the underlying design rationale of AN-RPL, namely that strategically distributed anchor nodes reduce the average topological distance between mobile nodes and stable DODAG roots. Consequently, fewer

forwarding operations are required, contributing to lower transmission delay and reduced per-packet communication cost.



**Figure 8.** Average hop count per successfully delivered packet across the four evaluated scenarios.

The four evaluated performance metrics exhibit a clear causal relationship that explains the observed performance improvements. Strategically deploying additional anchor nodes primarily shortens the average topological distance between mobile nodes and stable DODAG roots. Combined with the proposed Root-First Preference Principle, this improves parent selection stability and substantially reduces parent churn. More stable routing minimizes route reconstruction periods during which packets are frequently lost, thereby improving the Data Delivery Ratio. At the same time, fewer parent changes reduce control-message exchanges and radio-on time, while shorter routing paths decrease forwarding operations and retransmissions, resulting in lower energy consumption. Notably, the 89.5% reduction in parent churn observed under MRHOF between S2 and S4 is accompanied by a 25.9 percentage-point improvement in DDR, providing strong empirical support for the proposed routing mechanism. Collectively, these results demonstrate that the observed performance gains arise not only from additional infrastructure but also from the interaction between distributed anchor deployment and the Root-First Preference Principle, which together enhance routing robustness under node mobility.

## 5. Discussion

Beyond the quantitative improvements presented in Section 4, several broader insights can be drawn regarding the design of infrastructure-assisted routing for mobile IoT networks. AN-RPL improves routing performance through the complementary roles of infrastructure-assisted deployment and lightweight protocol enhancement rather than through either mechanism in isolation. From a deployment perspective, AN-RPL introduces an additional infrastructure cost associated with installing fixed anchor nodes. In practical IoT deployments, anchor nodes may be implemented using gateway-class platforms (e.g., Raspberry Pi 4 or equivalent single-board computers) equipped with IEEE 802.15.4 radio modules and connected through reliable backbone technologies such as Ethernet, Wi-Fi, or cellular networks. Because anchor nodes operate independently without exchanging routing information, the proposed architecture avoids additional coordination overhead while remaining compatible with existing RPL implementations. This makes AN-RPL particularly attractive for smart-building, campus, industrial, and similar deployments where fixed infrastructure is already available or can be deployed at relatively low cost.

The experimental results also reveal a clear cost-performance trade-off. Although increasing the number of anchor nodes consistently improves routing performance, the marginal benefit gradually decreases as anchor density increases. For example, under MRHOF, introducing a second anchor increases DDR by approximately 20.0 percentage points, whereas doubling the number of anchors from two to four yields a further improvement of only 5.9 percentage points. This pattern indicates diminishing marginal returns, suggesting

that the initial deployment of distributed anchor nodes provides the greatest practical benefit. Consequently, anchor-node density should be selected based on deployment requirements and infrastructure cost rather than maximized indiscriminately.

Although AN-RPL is architecturally designed to support scalable deployments through independently operating anchor nodes, the current validation is limited to a network of 25 mobile nodes under moderate pedestrian mobility (1–2 m/s). Future evaluations involving larger node populations, denser deployments, and more diverse mobility patterns, including vehicular scenarios and real mobility traces, are necessary to establish the practical scalability and robustness of the proposed approach under realistic operating conditions.

Finally, the current evaluation compares AN-RPL only against baseline RPL configurations using the OF0 and MRHOF objective functions. Although this comparison clearly demonstrates the benefits of the proposed infrastructure-assisted design over conventional RPL, it does not provide direct benchmarking against representative mobility-aware RPL enhancements discussed in Section 2. Comprehensive experimental comparisons with protocols such as Co-RPL, ME-RPL, EMA-RPL, MP-RPL, QFS-RPL, MSE-RPL, and RM-RPL under identical mobility models, network densities, and traffic conditions would provide a more complete assessment of the relative advantages and trade-offs of AN-RPL. Such evaluations represent an important direction for future research.

## 6. Conclusions

This paper presented and evaluated Anchor-Node RPL (AN-RPL), a lightweight infrastructure-assisted enhancement to the standard RPL protocol for mobile IoT environments. By strategically deploying a small number of fixed anchor nodes as distributed DODAG roots while requiring only minimal firmware modification on mobile sensor nodes, AN-RPL improves routing robustness without substantially increasing protocol complexity. Simulation results under four deployment scenarios and two objective functions (OF0 and MRHOF) demonstrate consistent improvements in communication reliability, routing stability, routing efficiency, and energy efficiency compared with the conventional single-root mobile RPL architecture. Overall, the findings suggest that infrastructure-assisted anchor-node deployment provides a practical and deployment-ready approach for enhancing RPL performance in mobile IoT networks while preserving the lightweight characteristics of the standard protocol. Although the current evaluation is limited to moderate mobility, a network of 25 mobile nodes, and comparisons against baseline RPL configurations, future work will focus on larger-scale deployments, more diverse mobility scenarios, real-world testbeds, and direct comparisons with representative mobility-aware RPL protocols.

**Author Contributions:** Conceptualization: T.C.V. and M.T.N.; Methodology: T.C.V.; Software: M.D.N.; Validation: L.Q.D., D.T.N. and M.D.N.; Formal analysis: T.C.V.; Investigation: D.M.N.; Resources: T.C.V.; Data curation: M.D.N.; Writing—original draft preparation: T.C.V.; Writing—review and editing: M.T.N.; Visualization: L.Q.D. and D.M.N.; Supervision: T.C.V.; Project administration: M.T.N.; funding acquisition: T.C.V. All authors have read and agreed to the published version of the manuscript.

**Funding:** Authors state no external funding involved.

**Data Availability Statement:** Data can be provided upon request.

**Acknowledgments:** The authors would like to thank Thai Nguyen University (ĐH2024-NV-06), Thai Nguyen University of Technology (TNUT), Viet Nam for the support.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

- [1] N. Monios, N. Peladarinos, V. Cheimaras, P. Papageorgas, and D. D. Piromalis, “A Thorough Review and Comparison of Commercial and Open-Source IoT Platforms for Smart City Applications,” *Electronics*, vol. 13, no. 8, p. 1465, Apr. 2024, doi: 10.3390/electronics13081465.
- [2] M. T. Nguyen, “Distributed compressive and collaborative sensing data collection in mobile sensor networks,” *Internet of Things*, vol. 9, p. 100156, Mar. 2020, doi: 10.1016/j.iot.2019.100156.
- [3] A. Brandt *et al.*, “RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks,” Mar. 2012. doi: 10.17487/rfc6550.

- [4] A. Oliveira and T. Vazão, “Low-power and lossy networks under mobility: A survey,” *Comput. Networks*, vol. 107, pp. 339–352, Oct. 2016, doi: 10.1016/j.comnet.2016.03.018.
- [5] M. T. Nguyen and H. R. Boveiri, “Energy-efficient sensing in robotic networks,” *Measurement*, vol. 158, p. 107708, Jul. 2020, doi: 10.1016/j.measurement.2020.107708.
- [6] H. Kharrufa, H. A. A. Al-Kashoash, and A. H. Kemp, “RPL-Based Routing Protocols in IoT Applications: A Review,” *IEEE Sens. J.*, vol. 19, no. 15, pp. 5952–5967, Aug. 2019, doi: 10.1109/JSEN.2019.2910881.
- [7] K. A. Darabkh, M. Al-Akhras, J. N. Zomot, and M. Atiquzzaman, “RPL routing protocol over IoT: A comprehensive survey, recent advances, insights, bibliometric analysis, recommendations, and future directions,” *J. Netw. Comput. Appl.*, vol. 207, p. 103476, Nov. 2022, doi: 10.1016/j.jnca.2022.103476.
- [8] Z. Shah, A. Levula, K. Khurshid, J. Ahmed, I. Ullah, and S. Singh, “Routing Protocols for Mobile Internet of Things (IoT): A Survey on Challenges and Solutions,” *Electronics*, vol. 10, no. 19, p. 2320, Sep. 2021, doi: 10.3390/electronics10192320.
- [9] O. Gaddour, A. Koubaa, R. Rangarajan, O. Cheikhrouhou, E. Tovar, and M. Abid, “Co-RPL: RPL routing for mobile low power wireless sensor networks using Corona mechanism,” in *Proceedings of the 9th IEEE International Symposium on Industrial Embedded Systems (SIES 2014)*, Jun. 2014, pp. 200–209. doi: 10.1109/SIES.2014.6871205.
- [10] I. El Korbi, M. Ben Brahim, C. Adjih, and L. A. Saidane, “Mobility Enhanced RPL for Wireless Sensor Networks,” in *2012 Third International Conference on The Network of the Future (NOF)*, Nov. 2012, pp. 1–8. doi: 10.1109/NOF.2012.6463993.
- [11] M. Bouaziz, A. Rachedi, A. Belghith, M. Berbineau, and S. Al-Ahmadi, “EMA-RPL: Energy and mobility aware routing for the Internet of Mobile Things,” *Futur. Gener. Comput. Syst.*, vol. 97, pp. 247–258, Aug. 2019, doi: 10.1016/j.future.2019.02.042.
- [12] F. Soma, I. El Korbi, and L. A. Saidane, “Mobility support over RPL using sensor nodes speed classification,” in *2016 IEEE/ACS 13th International Conference of Computer Systems and Applications (AICCSA)*, Nov. 2016, pp. 1–6. doi: 10.1109/AICCSA.2016.7945688.
- [13] M. Alilou, A. Babazadeh Sangar, K. Majidzadeh, and M. Masdari, “QFS-RPL: mobility and energy aware multi path routing protocol for the internet of mobile things data transfer infrastructures,” *Telecommun. Syst.*, vol. 85, no. 2, pp. 289–312, Feb. 2024, doi: 10.1007/s11235-023-01075-5.
- [14] A. Vaezian and Y. Darmani, “MSE-RPL: Mobility Support Enhancement in RPL for IoT Mobile Applications,” *IEEE Access*, vol. 10, pp. 80816–80832, 2022, doi: 10.1109/ACCESS.2022.3194273.
- [15] A. Seyfollahi, M. Mainuddin, T. Taami, and A. Ghaffari, “RM-RPL: reliable mobility management framework for RPL-based IoT systems,” *Cluster Comput.*, vol. 27, no. 4, pp. 4449–4468, Jul. 2024, doi: 10.1007/s10586-023-04199-0.
- [16] P. Arivubrahan and G. R. Kanagachidambaresan, “K-Trickle: performance evaluation and impact on quality of service in resource-constrained networks,” *Int. J. Data Sci. Anal.*, vol. 19, no. 4, pp. 783–792, May 2025, doi: 10.1007/s41060-024-00531-y.
- [17] A. Triantafyllou, P. Sarigiannidis, and T. D. Lagkas, “Network Protocols, Schemes, and Mechanisms for Internet of Things (IoT): Features, Open Challenges, and Trends,” *Wirel. Commun. Mob. Comput.*, vol. 2018, no. 1, pp. 1–24, Jan. 2018, doi: 10.1155/2018/5349894.
- [18] A. J. Dey and H. K. D. Sarma, “Routing Techniques in Internet of Things: A Review,” in *Trends in Communication, Cloud, and Big Data*, vol. 99, Springer, 2020, pp. 41–50. doi: 10.1007/978-981-15-1624-5\_5.
- [19] A. P., H. S. Vimala, and S. J., “Comprehensive review on congestion detection, alleviation, and control for IoT networks,” *J. Netw. Comput. Appl.*, vol. 221, p. 103749, Jan. 2024, doi: 10.1016/j.jnca.2023.103749.
- [20] A. Jahangeer, S. U. Bazai, S. Aslam, S. Marjan, M. Anas, and S. H. Hashemi, “A Review on the Security of IoT Networks: From Network Layer’s Perspective,” *IEEE Access*, vol. 11, pp. 71073–71087, 2023, doi: 10.1109/ACCESS.2023.3246180.
- [21] Z. Ghanbari, N. J. Navimipour, M. Hosseinzadeh, H. Shakeri, and A. Darwesh, “A New Lightweight Routing Protocol for Internet of Mobile Things Based on Low Power and Lossy Network Using a Fuzzy-Logic Method,” *Pervasive Mob. Comput.*, vol. 97, p. 101872, Jan. 2024, doi: 10.1016/j.pmcj.2023.101872.
- [22] V. C. Diniesh, B. Palaniswamy, L. Murali, N. Manikandan, and K. Ramaswamy, “Improved energy efficient load balanced mobility management RPL protocol for mobile internet of things networks,” *Sci. Rep.*, vol. 15, no. 1, p. 43199, Nov. 2025, doi: 10.1038/s41598-025-27253-w.
- [23] M. Ebrahim, M. Al-Rudaini, and W. Mardini, “A Tutorial for BonnMotion with Contiki Cooja,” *Research Gate*. 2017. doi: 10.13140/RG.2.2.24297.29281.
- [24] P. Thubert, “Objective Function Zero for the Routing Protocol for Low-Power and Lossy Networks (RPL),” Mar. 2012. doi: 10.17487/rfc6552.
- [25] O. Gnawali and P. Levis, “The Minimum Rank with Hysteresis Objective Function,” Sep. 2012. doi: 10.17487/rfc6719.