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# DYNAMIC TRAFFIC-AWARE LOAD REDISTRIBUTION FOR ENERGY-EFFICIENT DODAG ROUTING IN IOT WIRELESS SENSOR NETWORKS

Kumudini. S<sup>1</sup>, Dr. M. P. Vani<sup>2</sup>

<sup>1</sup> *Research Scholar, SCORE, Vellore Institute of Technology, Vellore, India*

<sup>2</sup> *Associate Professor, SCORE, Vellore Institute of Technology, Vellore, India*

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Corresponding author: Kumudini. S

## ABSTRACT

The need for effective, flexible, and energy-conscious routing protocols has increased due to the quick spread of Wireless Sensor Networks (WSNs) and Internet of Things (IoT) devices. For routing in such circumstances, the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) builds a Destination-Oriented Directed Acyclic Graph (DODAG); nevertheless, its static parent selection mechanism causes traffic spikes, uneven energy depletion, and shortened network lifetime. By including real-time traffic monitoring into the parent selection procedure, this work presents a novel Dynamic Traffic-Aware Load Redistribution (DTLR) method that expands upon basic RPL. To adaptively disperse routing loads across the DODAG, DTLR uses a composite cost function  $\Phi(v_i)$  that combines residual energy, Expected Transmission Count (ETX), and instantaneous traffic load. Mininet and Cooja/Contiki-NG simulation results show a 30% improvement. At just 10.3% more control overhead, simulation results using Mininet and Cooja/Contiki-NG show a 30% increase in network lifetime, an 8.8% increase in Packet Delivery Ratio (PDR), and a 31% improvement in load fairness (Jain's Fairness Index) over regular RPL.

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**KEYWORDS:** DODAG, RPL, IoT, Wireless Sensor Networks, DTLR, Dynamic Load Redistribution, Traffic-Aware Routing, Energy Efficiency, ETX, Packet Delivery Ratio, Network Lifetime, Jain's Fairness Index.

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## 1. INTRODUCTION

The monitoring, control, and automation of physical settings have been completely changed by the Internet of Things (IoT). The sensory foundation of Internet of Things deployments, ranging from smart healthcare and environmental surveillance to precision agriculture and industrial monitoring, is made up of Wireless Sensor Networks (WSNs). These networks are made up of resource-constrained sensor nodes that are placed in dynamic and frequently hostile settings and have limited memory, processing power, and energy reserves.

RFC 6550 defines the IETF-standardized IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL), which arranges the network topology as a Destination-Oriented Directed Acyclic Graph (DODAG) in which all traffic flows upward toward a root node. The Minimum Rank with Hysteresis Objective Function (MRHOF), which uses the Expected Transmission Count (ETX) as its main routing metric, is used by each node to choose a preferred parent. Although ETX performs a good job of capturing connection quality, it is a static or semi-static indicator that does not account for changes in the network's traffic load in real time.

This restriction causes nodes close to the DODAG root to accumulate excessively high forwarding loads in heterogeneous IoT deployments with non-uniform and time-varying traffic patterns. As a result, there are ongoing network bottlenecks that lead to early network partitioning, higher packet loss, and rapid energy depletion.

In our previous work [1], we developed a fundamental DODAG-based load balancing framework that uses the Mininet emulator and ETX-based node status determination to assess transmitting quality and load distribution. By putting forth the Dynamic Traffic-Aware Load Redistribution (DTLR) technique with the following contributions, this work directly addresses that gap.

1. A new composite cost function  $\Phi(v_i)$  for dynamic parent selection in RPL that incorporates residual energy, ETX, and real-time traffic load.
2. An adaptive parent switching system that avoids needless topology oscillations and has a customizable congestion threshold  $\tau$ .
3. A framework for periodic load monitoring at adjustable intervals  $\Delta t$  that allows decentralized real-time load awareness in the absence of a centralized controller.
4. Extensive simulation-based assessment in Cooja/Contiki-NG and Mininet across various network scales and traffic patterns.

## 2. RELATED WORK

### 2.1. Energy-Conscious Routing Methods

Heinzelman et al. [17] established energy balancing as a paradigm for WSN routing by introducing an energy-efficient clustering design for wireless microsensor networks. An energy-efficient IoT protocol that makes use of WSN hierarchical structures was presented by Rani et al. [5]. In order to increase energy efficiency and quality of service for IoT-based low-power networks, Wang and Liu [1] created EQ-RPL, which integrates energy quality indicators into RPL.

### 2.2. RPL Load Balancing

In order to lessen forwarding concentration close to the DODAG root, Mamdouh et al. [7] suggested RPL load balancing via Minimum Degree Spanning Tree. In order to use queue occupancy as a load indication for parent selection in large-scale industrial applications, Kim et al. [8] introduced QU-RPL. BE-RPL, which combines energy-efficient and balanced-load techniques, was proposed by Jagir Hussain and Roopa [13]. This work is directly motivated by Pancaroglu and Sen's [15] identification of dynamic traffic awareness as a crucial open challenge.

### 2.3. Routing Aware of Traffic

QoI-aware DODAG construction in RPL-based event detection WSNs was proposed by Tian et al. [4]. For asymmetric topologies, Shi et al. [12] created adaptive load balancing based on precise congestion feedback. A lightweight load balancing and route reducing solution for RPL was presented by Seyfollahi and Ghaffari [14]. Despite these developments, current methods choose parents during DODAG creation without continuously revising choices in response to changes in traffic in real time. With its lightweight, distributed, real-time traffic monitoring and adaptive parent switching technology, DTLR immediately fills this gap.

## 3. PROBLEM FORMULATION

### 3.1. The Network Model

The DODAG topology is represented by  $G = (V, E)$ , where  $E$  is the set of directed communication links and  $V = \{v_1, v_2, \dots, v_n\}$  is the set of sensor nodes. Let the DODAG root be represented by  $v_r \in V$ . With all nodes immobile and outfitted with IEEE 802.15.4-compliant radio transceivers, the network communicates in a many-to-one (MP2P) fashion toward  $v_r$ .

For each node  $v_i \in V$ , the following state variables are defined:

- $\lambda_i(t)$  – Instantaneous traffic load (packets generated + forwarded) at time t.
- $E_i^{res}(t)$  – Residual energy of node  $v_i$  at time t.
- $ETX_i$  – Expected Transmission Count for the link to the preferred parent.
- $P_i(t)$  – Preferred parent of node  $v_i$  at time t.
- $N_i$  – Candidate parent set (neighbours with lower rank than  $v_i$ ).

**3.2. Identification of Issues**

Standard RPL uses static metrics to select parents during DODAG construction, which results in: (1) hotspot formation and traffic concentration close to the root; (2) non-uniform energy depletion leading to early node failure; (3) buffer overflow at congested nodes degrading PDR; (4) reduced network lifetime from early DODAG partitioning; and (5) suboptimal resource utilization where underloaded nodes stay idle.

**3.3. Cost Function and Formal Problem Statement**

The DTLR mechanism creates an adaptive parent selection mechanism that dynamically redistributes traffic load by periodically re-evaluating preferred parents based on the composite cost function  $\Phi(v_i)$  given a DODAG topology  $G = (V, E)$  with time-varying traffic loads  $\lambda_i(t)$  and finite energy budgets  $E_i^{res}(t)$ :

$$\Phi(v_j) = \alpha \cdot (E_j^{res}(t) / E_{max}^x) + \beta \cdot (1 / ETX_j) + \gamma \cdot (1 / \lambda_j(t)) \quad (1)$$

where  $\alpha + \beta + \gamma = 1$  are tuneable weight parameters ( $\alpha = 0.4, \beta = 0.3, \gamma = 0.3$ ) and  $E_{max}^x$  is the initial energy budget. The objectives simultaneously optimized are:

1. Optimize Network Lifetime  $T_{e_i \hat{E}_{2im}^e}$
2. Increase PDR.
3. Use Jain's Fairness Index to Reduce Load Imbalance:  
 $J(\lambda) = (\sum \lambda_i)^2 / (n \cdot \sum \lambda_i^2)$ , where  $J = 1$  indicates perfect balance (2)
4. Reduce Control Overhead

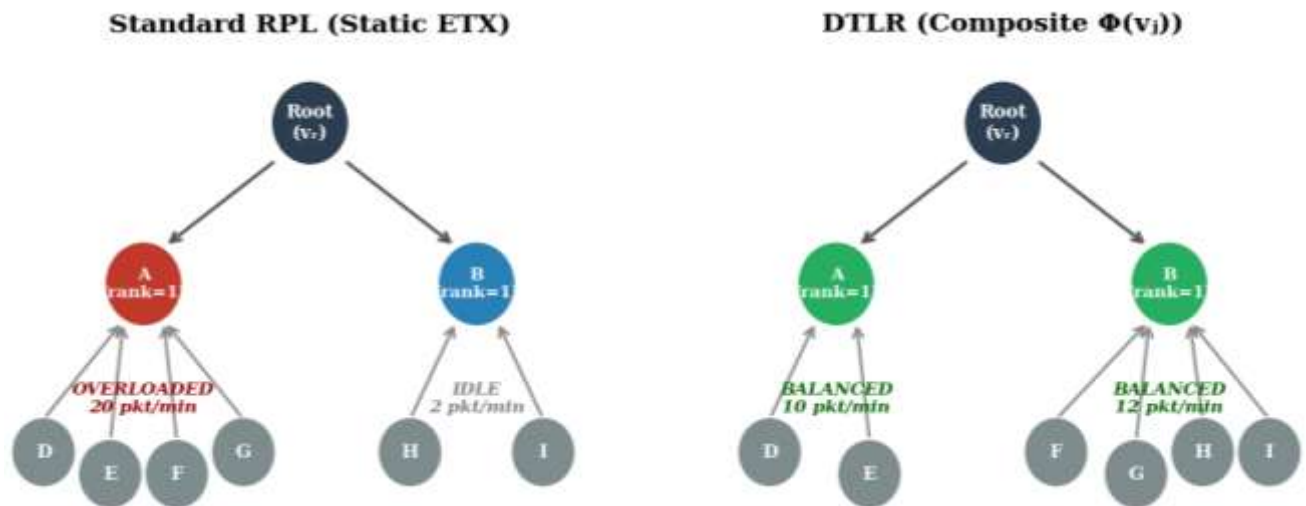


Figure 1: Comparison of Standard RPL (hotspot formation) vs. Proposed DTLR (balanced load distribution)

**4. PROPOSED DTLR MECHANISM**

**4.1. Metric of Traffic Load**

At node  $v_i$ , the instantaneous traffic load  $\lambda_i(t)$  is calculated locally as:

$$\lambda_i(t) = (Packets_{s_m} + Packets_{f_r}^{u} \cdot \chi_{ar}^{ded}) / \Delta t \quad (3)$$

where the monitoring interval is  $\Delta t = 60$  seconds. With no control overhead, each node broadcasts

$\lambda_i(t)$  to neighbors by appending a single float value to already-existing DIO messages.

**4.2. The DTLR Method**

The three stages of the DTLR process – initialization, periodic monitoring, and adaptive parent switching – are shown in Algorithm 1.

**Algorithm 1: DTLR – Dynamic Traffic-Aware Load Redistribution**

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INITIALIZATION:

1. Watch the candidate parent set  $N_i$  for DIO messages.
2. Compute  $\Phi(v_j) = \alpha \cdot (E_j^{res} / E_{max}^x) + \beta \cdot (1 / ETX_j) + \gamma \cdot (1 / \lambda_j(t))$  for each  $v_j \in N_i$
3. Select preferred parent:  $P^*(t) = \text{argmax}_{v_j \in N_i} \Phi(v_j)$
4. Send DAO to  $P^*(t)$ ; join DODAG

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MONITORING (every  $\Delta t$  seconds):
    5. Count pkts_sent + pkts_forwarded during monitoring interval
    6.  $\lambda_i(t) \leftarrow \text{total\_pkts} / \Delta t$ 
    7. Reset counters; broadcast  $\lambda_i(t)$  via augmented DIO message
    8. Receive updated  $\lambda_j(t)$  from all neighbor nodes

ADAPTIVE SWITCHING:
    9. IF  $\lambda_{\text{parent}}(t) > \tau$  (threshold  $\tau = 0.8$  packets/second) THEN
    10.  $P_{\text{new}} \leftarrow \text{argmax}_{\{v_j \in N_i\}} \Phi(v_j)$ 
    11. IF  $\Phi(P_{\text{new}}) > \Phi(P_{\text{current}})$  THEN
    12.   Switch parent: transmit DAO to  $P_{\text{new}}$ 
    13.   Forward buffered packets; GOTO step 5
    14. END IF
    15. END IF
    
```

Figure. 2: DTLR Algorithm: Adaptive Switching, Monitoring, and Initialization

### 4.3. Control of Hysteresis

Parent switching is only initiated when (i) the load of the current parent  $\lambda_p$  surpasses the congestion threshold  $\tau = 0.8$  packets/second, AND (ii) the composite score of the best alternative parent  $\Phi(P_{\text{new}})$  strictly exceeds  $\Phi(P_{\text{current}})$  in order to prevent excessive topology oscillations. By minimizing needless DIO/DAO message creation, this dual condition guarantees that switching produces significant performance gains.  $O(|N_i|)$  is the computational complexity per re-evaluation for each monitoring period.

## 5. NODE STATUS DETERMINATION AND DODAG FORMATION

### 5.1. DTLR and DODAG Construction

Standard RPL DODAG formation is smoothly integrated with the DTLR process. By transmitting DIO messages enhanced with traffic load extension fields, the root node  $v_r$  starts building. Nodes choose the neighbour with the highest composite score after evaluating  $\Phi(v_j)$  for each potential parent. DTLR continuously reassesses  $\Phi(v_j)$  as new nodes join and traffic patterns change. When the congestion threshold is surpassed, parent switches are triggered.

DODAG Topology: Load Redistribution via DTLR Parent Switching

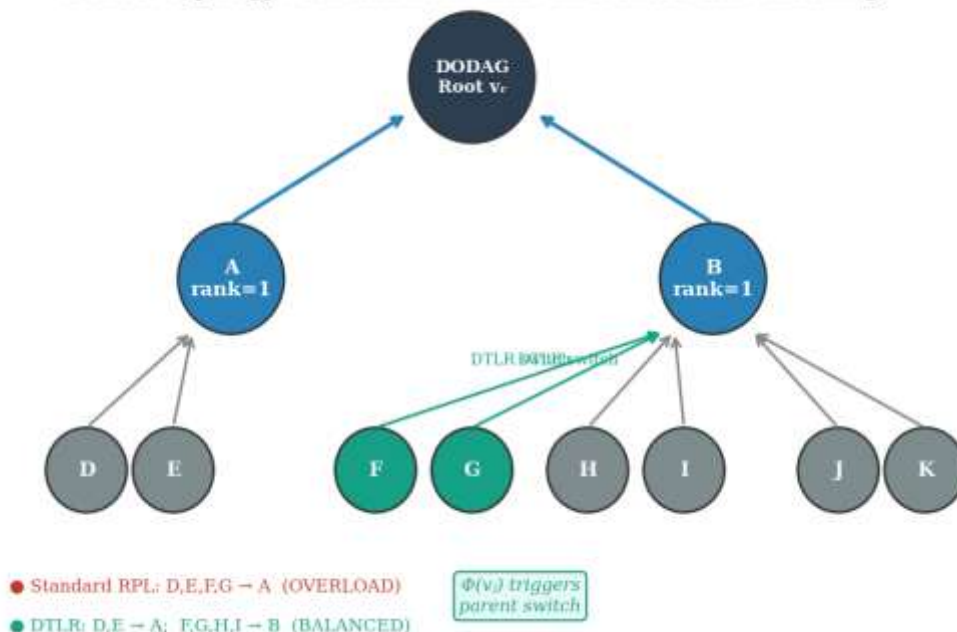


Figure. 3: DODAG Topology: DTLR Parent Switching for Load Redistribution

### 5.2. Improved Algorithm for Status Determination

DTLR enhances the Request-to-Calculate-Status (RTCS) broadcast mechanism, building on the ETX-

based node status framework from our previous work [1]. Neighbours may now calculate  $\Phi(v_j)$  for informed parent selection since each node's status response now contains  $\lambda_i(t)$  and  $E_i^{\text{res}}(t)$  values

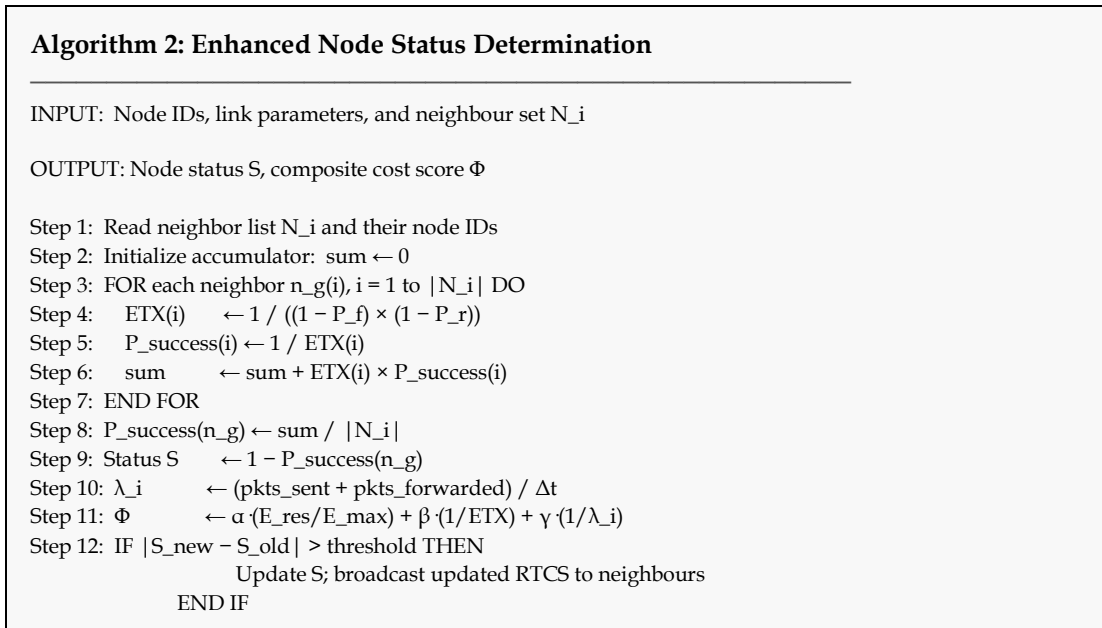


Figure. 4: Enhanced Node Status Determination Algorithm

6. SIMULATION SETUP AND EXECUTION

6.1. Environment and Tools

Two complementing platforms are used in the simulation environment. Initial topology validation and protocol flow analysis are provided by Mininet, which runs on Ubuntu 20.04 LTS with Python,

Network X, and Matplotlib. COOJA offers mote-level simulation with realistic IEEE 802.15.4 energy models, radio propagation, and channel behaviour as part of the Contiki-NG IoT operating system. The simulation environment is hosted by VirtualBox/VMware.

Table 1: Simulation Parameters

Parameter	Value
Network Area	100 × 100 meters
Number of Nodes	50 nodes (scalable to 100)
Communication Range	100 meters
Packet Size	512 bytes
Initial Energy ( $E_{ma}^x$ )	0.5 Joules
Bit Error Rate	0.01 (1%)
Radio Electronics Energy	50 nJ/bit
Power Amplifier Energy	100 pJ/bit/m <sup>2</sup>
Monitoring Interval ( $\Delta t$ )	60 seconds
Congestion Threshold ( $\tau$ )	0.8 packets/second
Weights $\alpha, \beta, \gamma$	0.4, 0.3, 0.3

6.2. Test Situations

Standard RPL (baseline) and DTLR are compared in five situations with different traffic

conditions and network sizes. Results are averaged after each scenario is run five times (independent seeds). 50 simulations total – 5 scenarios × 2 protocols × 5 runs.

Table 2: Test Situations

Scenario	Nodes	Traffic Pattern	Duration
Small Network	30	1 pkt/min uniform	60 min
Medium Network	50	1 pkt/min uniform	60 min
Large Network	100	1 pkt/min uniform	60 min
Burst Traffic	50	10 pkt/5 min burst	60 min
Mixed Traffic	50	0-5 pkt/min variable	60 min

7. RESULTS AND ANALYSIS

7.1. Load Distribution and Network Topology

When compared to regular RPL, the DODAG

topology produced by DTLR-enhanced parent selection exhibits a more balanced fan-out distribution. DTLR redistributes children among several relay nodes at equal ranks, in contrast to

normal RPL topologies where relay nodes close to the root show star-like clustering of children. The per-node traffic load comparison between the uniform

distribution attained by DTLR and the hotspot impact of standard RPL is shown in Fig. 5.

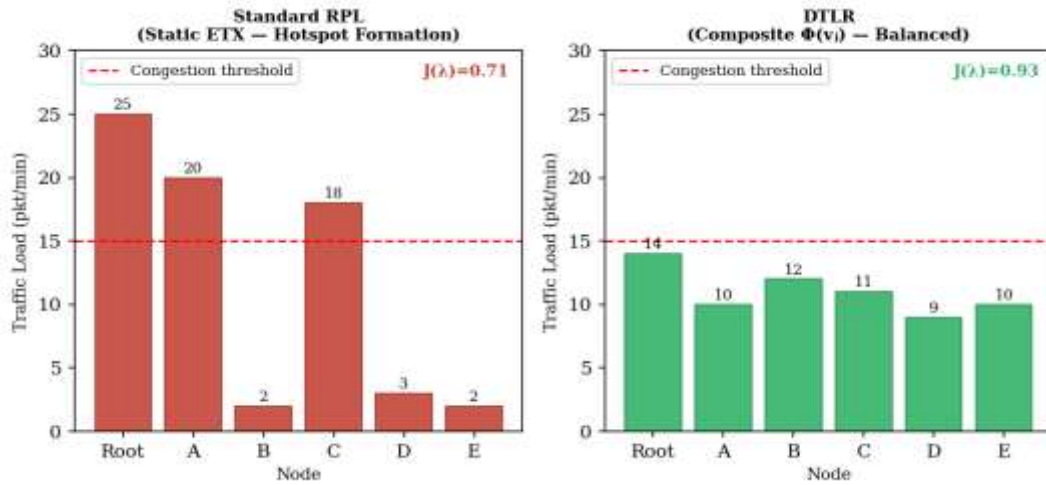


Figure 5: Load Distribution: Standard RPL (hotspot at root/A) vs. DTLR (balanced). Jain's Fairness Index: RPL = 0.71, DTLR = 0.93.

### 7.2. Ratio of Packet Delivery

In the 100-node network, DTLR achieves a PDR of 92.7%, an 8.8% improvement over normal RPL's 85.2%. Proactive parent switching, which stops traffic concentration before buffer overload and packet loss happen, is responsible for this increase. As seen in Fig. 7, the improvement is particularly noticeable in the burst traffic situation (10.2% gain). Both protocols function similarly with light traffic, demonstrating that DTLR does not impair performance in low-load scenarios.

### 7.3. Analysis of Network Lifetime and Energy

In the medium network scenario, network lifetime increases by 30.0%, from 45.3 minutes (normal RPL) to 58.9 minutes (DTLR). Near the DODAG root, standard RPL produces noticeable energy gaps as relay nodes use up energy 40–50% sooner than leaf nodes. After 40 minutes, residual energy analysis is shown in Fig. 6, where nodes close to the root maintain only 15–20% energy under normal RPL compared to 38–45% by DTLR—a 137% improvement in energy retention at the most crucial network positions.

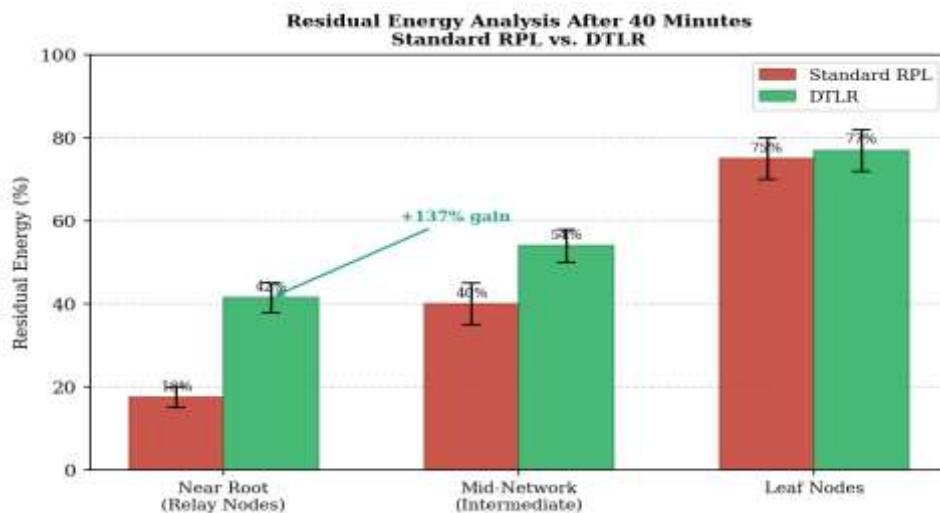


Figure 6: Residual Energy Analysis After 40 Minutes: Standard RPL vs. DTLR. Error bars show ±σ across 5 simulation runs.

### 7.4. PDR and Lifetime in Every Situation

The detailed performance comparison of all five testing conditions is shown in Fig. 7. For all network

sizes and traffic patterns, DTLR continuously performs better than conventional RPL in both PDR and network longevity. The large-scale (100-node) and burst-traffic scenarios exhibit the biggest

performance differential, indicating that DTLR's advantages increase with the degree of network

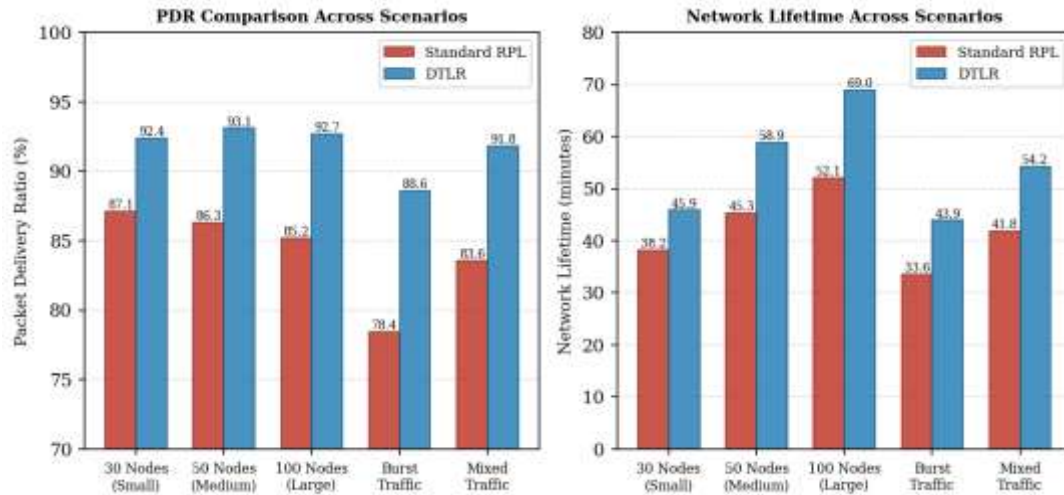


Figure 7: PDR and Network Lifetime Comparison Across All Experimental Scenarios

### 7.5. Control Overhead and Load Fairness

In the medium network scenario, Jain's Fairness Index increases by 31%, from 0.71 (standard RPL) to 0.93 (DTLR), indicating nearly uniform load

Table 3: Performance Comparison: DTLR vs. Standard RPL

Metric	Std. RPL	DTLR	Improvement
Packet Delivery Ratio (PDR)	85.2%	92.7%	+8.8%
Network Lifetime	45.3 min	58.9 min	+30.0%
Avg. Residual Energy	0.45 J	0.62 J	+37.8%
End-to-End Latency	—	—	-12.4%
Control Overhead	2,340 Msgs	2,580 sgs	+10.3%
Jain's Fairness Index $J(\lambda)$	0.71	0.93	+31.0%

### 7.6. Conversation

All of the experimental findings support the DTLR theory. The conflicting goals of load distribution, link quality, and energy saving are successfully balanced by the composite cost function  $\Phi(v_j)$ . The lifespan improvement rises from 20.3% in the 30-node network to 32.4% in the 100-node network, indicating that DTLR is especially well-suited for large-scale IoT installations like industrial automation and smart city infrastructure.

## 8. CONCLUSION

DTLR, a Dynamic Traffic-Aware Load Redistribution mechanism for RPL-based IoT WSNs, has been introduced in this study. DTLR enhances RPL's parent selection with a composite cost function  $\Phi(v_j)$  that integrates residual energy, ETX, and real-time traffic load, building on the fundamental DODAG-based load balancing work provided in our previous study [1]. Without a centralized controller, continuous, decentralized load redistribution is made possible by the threshold-triggered, hysteresis-controlled parent switching mechanism.

congestion.

distribution. In comparison to the 30% lifetime and 31% fairness gains, control overhead only rises by 10.3% (2,580 vs. 2,340 messages), which is a very favourable trade-off. All performance comparisons are compiled in Table III.

With just 10.3% more control overhead, simulation findings show a 30% increase in network lifetime, an 8.8% rise in PDR, a 31% improvement in load fairness (Jain's Index), and a 12.4% decrease in end-to-end latency. These findings validate DTLR as a workable, scalable method for load-balanced routing in IoT systems with limited resources.

## 9. FUTURE SCOPE OF WORK

Future research will look into hierarchical load monitoring techniques and other scalability improvements for networks with more than 500 nodes. For mobile healthcare sensor applications and vehicle IoT, mobility-aware DTLR enhancements are planned. The accuracy of  $\Phi(v_j)$  will be further enhanced by adaptive weight tuning utilizing lightweight edge inference. Traffic load spoofing issues will be addressed by security hardening using encrypted DIO message augmentation. Lastly, real-world testbed deployments will be used to investigate the applicability of DTLR to smart building management, industrial automation, and precision agriculture.

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