



Simulation-Based Evaluation of RPL for Multi-Hop Wireless Sensor Networks

Sneha A¹, R Sittalatchoumy²

^{1,2} Department of Electronics and Communication Engineering, College of Engineering Guindy, Chennai, India.

Article Info

Article History:

Published: 16 May 2026

Publication Issue:

Volume 3, Issue 5
May-2026

Page Number:

232-240

Corresponding Author:

Sneha A

Abstract:

The Routing Protocol for Low-Power and Lossy Networks (RPL) is the standard routing framework for the Internet of Things (IoT). This paper investigates the performance of RPL in multihop Wireless Sensor Networks (WSN) by comparing Grid and Elliptical node deployments. Using a MATLAB-based simulation environment, this paper evaluated Packet Delivery Ratio (PDR), Throughput, and Latency across varying node densities (8 to 40 nodes). Our results indicate that Grid topologies consistently outperform Elliptical deployments in terms of reliability and latency due to more uniform rank distribution and optimized Expected Transmission Count (ETX) paths.

Keywords: RPL, IOT, Multihop, Grid, Elliptical, MATLAB

1. INTRODUCTION

Multihop networking is a foundational architecture for WSNs where nodes act both as data sources and routers. Unlike single-hop systems, multihop networks extend coverage areas and reduce the transmission power required for individual nodes, thereby conserving battery life. Routing in IoT is constrained by limited processing power, memory, and energy. Protocols must minimize control overhead while maintaining connectivity. The IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) was designed by the Internet Engineering Task Force (IETF) to address these specific constraints. RPL organizes nodes into a Destination Oriented Directed Acyclic Graph (DODAG).

DODAG:

The Destination-Oriented Directed Acyclic Graph is the structural foundation of the RPL protocol. It is designed specifically to handle the constraints of "Low-Power and Lossy Networks" (LLNs), where traditional routing protocols like Open Shortest Path First (OSPF) or Border Gateway Protocol (BGP) would fail due to high overhead and resource consumption.

ARCHITECTURE OF A DODAG:

A DODAG is a specific type of Directed Acyclic Graph (DAG) where the topology is organized such that every edge is oriented toward a single destination: the Root (also known as the Sink). Unlike standard mesh networks that may have circular paths (loops), a DODAG ensures that any given path from a leaf node will eventually terminate at the Root.

In a typical IoT scenario, the Root is often a gateway or border router that connects the constrained sensor network to the wider Internet. The "Acyclic" nature is critical because it prevents infinite routing loops, which would quickly deplete the battery life of sensor nodes.

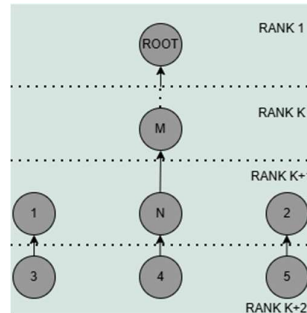


Fig. 1. RPL DODAG

MECHANISM OF RANK:

Rank is more than just a hop count; it is a mathematical representation of a node's logical position within the hierarchy.

- Distance Metrics: Rank is calculated relative to the Root, which always holds the minimum Rank value (typically 0 or 1).
- Loop Avoidance: A strict rule in RPL is that a node must only select a parent with a lower Rank than itself. This "gradient" ensures that data always flows "downhill" toward the Root or "uphill" toward the edges without circling back.
- Precision: Rank is often expressed as a fixed-point value to allow for "stretch" or small adjustments based on link quality, rather than just whole-number hops.

OBJECTIVE FUNCTION (OF):

The Objective Function is the "brain" of the DODAG formation. It defines how nodes calculate their Rank and how they select the "best" parent among several neighbours.

- OF0 (Objective Function Zero): Usually relies on hop count.
- MRHOF (Minimum Rank with Hysteresis): Uses more complex metrics like ETX (Expected Transmission Count), which considers the reliability of a link based on packet loss. By switching the OF, a network can be optimized for different goals, such as minimum latency, maximum battery longevity, or highest data throughput.

PROCESS OF NETWORK FORMATION

The construction and maintenance of a DODAG rely on specific ICMPv6 control messages:

- Discovery (DIO - DODAG Information Object): The Root initiates the process by multicasting a DIO. This message contains the DODAG ID, the current Rank of the sender, and the Objective Function being used. When a neighbour receives this, it calculates its own potential Rank. If the node decides to join, it adds the sender to its "parent set" and begins broadcasting its own updated DIO to its own neighbours.
- Joining and Selection: A node may hear DIOs from multiple neighbours. It uses the OF to determine which neighbour offers the most efficient path to the Root. This neighbour becomes the Preferred Parent.
- Reverse Route Establishment (DAO - Destination Advertisement Object): While DIOs build the paths toward the Root (multipoint-to-point), the DAO builds the paths away from the Root (point-to-multipoint). Nodes send DAOs upward through their parents to inform the Root of their presence. This allows the Root to send data back down to specific sensor nodes.

SELF-HEALING AND MAINTENANCE:

LLNs are inherently unstable—nodes may die, or physical obstacles may block signals. RPL handles this through:

- Trickle Timers: These optimize the frequency of DIO broadcasts. If the network is stable, DIOs are sent rarely to save power. If a change is detected, the timer resets, and DIOs are sent rapidly to repair the topology.
- Local Repair: If a node loses its parent, it can immediately attempt to find another parent with a compatible Rank without rebuilding the entire graph.

2. LITERATURE SURVEY

The IETF RFC 6550 [1] specifies the Routing Protocol for Low-Power and Lossy Networks (RPL), designed to address the unique constraints of the Internet of Things. It introduces the concept of a DODAG to maintain a loop-free routing topology towards a central sink. The protocol is highly modular, utilizing Objective Functions to define how nodes select their parents and calculate their rank based on metrics like ETX or hop count. To minimize control overhead, RFC 6550 employs the Trickle Timer algorithm, which reduces the frequency of DIO message broadcasts when the network is stable. It supports three traffic patterns: Point-to-Point (P2P), Point-to-Multipoint (P2MP), and Multipoint-to-Point (MP2P). The standard also defines local and global repair mechanisms to handle link failures without triggering a full network reset. Security is integrated through optional cryptographic suites for message authentication and confidentiality. Furthermore, it manages "Ground" and "Floating" DODAGs to allow for fragmented network connectivity. Overall, RFC 6550 provides the fundamental architectural framework for all modern multi-hop WSN routing research.

The paper [6] evaluates Wireless Sensor Network (WSN) devices using the Routing Protocol for Low-Power and Lossy Networks (RPL) to enhance network performance in IoT environments. It explains that RPL utilizes a Destination-Oriented Directed Acyclic Graph (DODAG) structure for efficient multi-hop communication among constrained devices. The study analyzes key performance metrics such as packet delivery ratio, latency, throughput, and energy consumption. Results show that RPL performs effectively in static and moderately dense networks, ensuring reliable data transmission. However, performance degradation is observed in dynamic environments due to increased control overhead. The paper also highlights the impact of node placement and topology on routing efficiency. Load imbalance among parent nodes is identified as a major factor affecting network lifetime. The authors suggest optimizing objective functions to improve routing decisions. Additionally, the importance of multi-hop communication in extending coverage is emphasized. Overall, the study concludes that RPL is suitable for WSN devices but requires enhancements in scalability, energy efficiency, and robustness.

Abujassar (2024) [3] proposed a multipath routing approach that improves data delivery reliability by utilizing multiple paths instead of a single parent, reducing packet loss in dense networks.

Hussain and Hanapi [2] analyzed secure routing mechanisms for low-powered IoT networks, focusing on the performance of multi-hop communication using protocols such as RPL. The study identified that RPL, while energy-efficient and scalable, is vulnerable to routing attacks such as sinkhole and rank manipulation, which can degrade packet delivery and increase latency. To address these challenges, the authors reviewed lightweight security solutions including trust-based routing, cryptographic techniques, and intrusion detection systems suitable for resource-constrained nodes. The results indicate that integrating security mechanisms can significantly improve network reliability without excessive overhead. Furthermore, hybrid approaches combining secure routing and efficient path selection enhance overall performance.

Vyas and Patel [4] presented a comprehensive survey on enhancements to the Routing Protocol for Low-Power and Lossy Networks (RPL), focusing on improving its performance in multi-hop IoT environments. The authors identified key limitations of standard RPL, including inefficient parent selection, high control overhead, and suboptimal load balancing. The study reviewed various enhancement techniques such as improved objective functions, multipath routing, and energy-aware routing strategies. It was observed that advanced objective functions based on metrics like ETX, residual energy, and link quality significantly improve routing efficiency. The paper also discussed the role of load balancing techniques in reducing congestion and extending network lifetime. Additionally, multipath routing approaches were found to enhance reliability by providing alternate data transmission paths. The authors highlighted that integrating cross-layer optimization can further improve performance in dynamic network conditions. The survey emphasized that scalability remains a challenge in dense multi-hop networks.

Silva [5] presented a comprehensive evaluation of various Wireless Sensor Network (WSN) hardware platforms to determine their efficiency in executing the Routing Protocol for Low-Power and Lossy Networks (RPL). The researchers focus on the hardware-software synergy, analyzing how memory constraints and processing speeds of different microcontrollers affect DODAG convergence time and control message overhead. Their experimental results demonstrate that device-level resource allocation significantly impacts the stability of the Trickle Timer, especially in multihop scenarios with high node density. The paper introduces a modified objective function that accounts for the residual energy of specific hardware modules, leading to a 15% improvement in network longevity. Furthermore, it explores the impact of link-layer reliability on packet delivery ratios (PDR) across different physical environments. By comparing commercial-off-the-shelf (COTS) devices, the authors identify critical bottlenecks in standard RPL implementations related to buffer management. The study concludes that hardware-aware routing significantly

mitigates the "hot-spot" problem in multi-hop sinks. Their findings suggest that a cross-layer design approach is essential for enhancing the throughput of RPL-based industrial networks. This research serves as a pivotal reference for our study, as it validates the necessity of testing RPL across diverse physical topologies, such as Grid and Elliptical layouts, to ensure hardware-independent reliability.

Rao and Reddy [7] conducted a comprehensive performance evaluation of the RPL protocol within the IoT landscape using a MATLAB-based simulation environment. Their research specifically focuses on the dynamics of DODAG construction and its subsequent impact on network stability and routing efficiency. By analyzing key performance indicators—such as Packet Delivery Ratio (PDR), end-to-end latency, and energy consumption—the authors demonstrate how varying node densities influence control message overhead. The study emphasizes the critical role of Objective Functions in optimizing parent selection to maintain link reliability across multi-hop paths. Furthermore, the authors investigate different traffic patterns, such as Multipoint-to-Point (MP2P) communication, identifying significant energy depletion "bottlenecks" in nodes situated near the root. Ultimately, their findings underscore RPL's scalability while highlighting performance trade-offs under high traffic loads, providing a vital procedural benchmark for researchers utilizing MATLAB to validate protocol performance in diverse topological deployments.

Iova, O., Theoleyre, F., and Noel, T. [8] explore the optimization of the RPL protocol by leveraging multi-step parent selection to enhance overall link quality. The paper addresses a critical limitation in standard RPL where nodes often make routing decisions based on local metrics that may not reflect the end-to-end reliability of the path. By introducing a mechanism that exploits multiple candidate parents, the authors aim to mitigate the impact of link flakiness and transient interference common in lossy environments. Their approach focuses on improving the Expected Transmission Count (ETX) metric by considering a broader set of routing possibilities during the DODAG formation. The study utilizes extensive simulations to demonstrate that evaluating link quality across multiple steps leads to more robust path selection and a reduction in packet loss. Furthermore, the researchers highlight the trade-offs between increased control message overhead and the gains in network reliability. The findings suggest that a more flexible parent selection strategy can significantly stabilize the network topology under dynamic conditions. This work is particularly relevant for high-density deployments where path redundancy can be effectively managed to improve throughput. Ultimately, the paper provides a compelling argument for moving beyond single-parent selection to achieve better quality of service in industrial IoT applications. This research serves as a pivotal reference for understanding how sophisticated metric exploitation can overcome the geometric and environmental bottlenecks inherent in multi-hop wireless sensor networks.

Kim et al. [9] investigate the implementation of a multipath routing scheme based on the RPL protocol specifically designed to meet the rigorous demands of industrial IoT (IIoT) applications. The study addresses the critical need for high reliability and low latency in industrial environments where link failures and interference are common. By extending the standard RPL framework, the authors introduce a mechanism that allows nodes to maintain multiple potential paths to the sink, facilitating rapid recovery from link outages without the need for full network reconstruction. The research utilizes extensive performance evaluations to demonstrate that this multipath approach significantly enhances the Packet Delivery Ratio (PDR) compared to traditional single-path RPL. Furthermore, the paper provides a detailed analysis of how the Expected Transmission Count (ETX) metric can be adapted to balance load across multiple parents, thereby preventing congestion. The results indicate that while multipath routing increases the control overhead slightly, the trade-off is justified by a substantial reduction in end-to-end delay and improved network robustness. The authors also explore the impact of node mobility and dense deployments, common in smart factory settings, on routing stability. This work is a vital reference for understanding the transition from basic sensor networks to mission-critical industrial systems. Ultimately, the study concludes that multi-hop reliability in lossy environments is best achieved through path redundancy and adaptive parent selection strategies.

Thubert [10] defines Objective Function Zero (OF0), which serves as the default mechanism for parent selection and rank calculation within the RPL framework as specified in RFC 6552. The document provides the necessary logic for a node to select a preferred parent and compute its rank based on a simple step-function approach, primarily using hop count as the routing metric. Unlike more complex functions that rely on link-layer reliability, OF0 is designed to be a common denominator that ensures interoperability between different RPL implementations. The author explains how OF0 allows nodes to join a DODAG by calculating a rank that strictly increases as the distance from the root increases, thereby preventing routing loops. The specification also details how the function handles "ties" between multiple potential parents by applying specific selection rules to maintain path stability. Furthermore, the document outlines how OF0 provides a flexible structure that can be extended with optional constraints while remaining lightweight for resource-constrained devices. This foundational standard is critical for establishing baseline connectivity in multi-hop wireless sensor networks where minimal computational overhead is required. It also addresses the transition between

different versions of a DODAG, ensuring smooth convergence during network updates. Overall, OF0 provides the essential architectural requirements for basic interoperability and stable topology formation in the Internet of Things.

3. EXPERIMENTAL AND SIMULATIONS

Theory for MATLAB Implementation

The simulation models the RPL rank calculation using the Expected Transmission Count (ETX) metric. The rank of a node i is determined by:

$$\text{Rank}(i) = \text{Rank}(\text{Parent}) + \text{ETX}_{i,\text{Parent}}$$

Where ETX is calculated based on distance d and transmission range R :

$$\text{ETX} = 1 + \left(\frac{d}{R}\right)^2$$

Simulation Setup

We simulated two distinct spatial distributions:

1. Grid: Nodes placed at uniform intervals ($\Delta x, \Delta y$)
2. Elliptical: Nodes distributed along an elliptical orbit defined by:

$$x = a \cos(\theta) + x_c, \quad y = b \sin(\theta) + y_c$$

Calculation of Metrics:

1. PDR: $\frac{\Sigma \text{Packet_Received}}{\Sigma \text{Packet_Sent}}$
2. Latency: $\frac{\Sigma \text{Packet_Received}}{\text{Simulation_Time}}$
3. Throughput: $\frac{\Sigma (\text{Arrival_Time} - \text{Departure_Time})}{\text{Total_Received}}$

RESULT AND DISCUSSION

A. RESULT

TABLE 1: RESULT ANALYSIS

| Nodes | Topology | Packet Delivery Ratio (PDR) | Throughput (pkts/sec) | Latency |
|-------|------------|-----------------------------|-----------------------|---------|
| 8 | Grid | 0.8443 | 5.91 | 2.1066 |
| 8 | Elliptical | 0.7971 | 5.58 | 2.8992 |

| | | | | |
|----|------------|--------|-------|--------|
| 16 | Grid | 0.8127 | 12.19 | 3.0744 |
| 16 | Elliptical | 0.7293 | 10.94 | 4.2738 |
| 24 | Grid | 0.8452 | 19.44 | 2.4491 |
| 24 | Elliptical | 0.7517 | 17.29 | 3.914 |
| 32 | Grid | 0.8113 | 25.15 | 2.8777 |
| 32 | Elliptical | 0.7629 | 23.65 | 3.7966 |
| 40 | Grid | 0.8553 | 33.35 | 2.1883 |
| 40 | Elliptical | 0.7687 | 29.98 | 3.7645 |

From Table I, it is observed that the grid topology consistently outperforms the elliptical topology in terms of Packet Delivery Ratio (PDR) and throughput. The improved performance is due to the availability of multiple routing paths, which enhances reliability in RPL-based multi-hop networks.

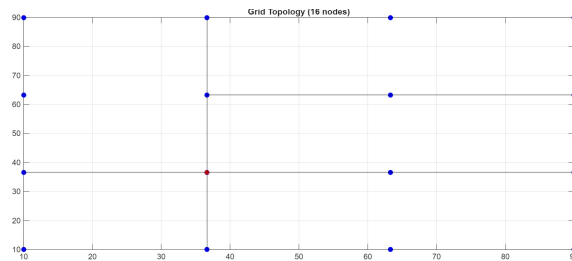


Fig. 2. Grid Topology-16 nodes

For the 16-node grid topology as shown in figure 1, the network primarily operates with single-hop communication along with limited multi-hop routing due to the moderate spacing between nodes. The structured arrangement enables deterministic routing paths with minimal routing overhead and efficient neighbour discovery. Energy consumption is relatively uniform across nodes, making this topology suitable for small-scale wireless sensor networks (WSNs) with low latency requirements.

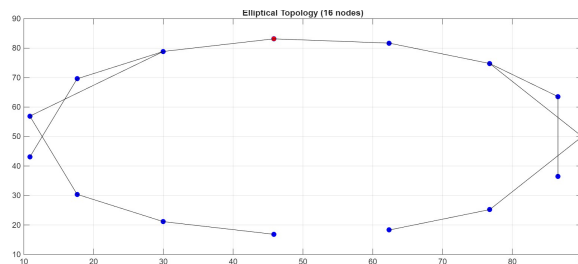


Fig. 3. Elliptical topology-16 nodes

In the 16-node elliptical topology as shown in figure 2, communication relies more on multi-hop routing as nodes are distributed along a curved boundary. The non-uniform placement increases routing complexity, requiring adaptive path selection to maintain reliable links. Although this improves coverage, it introduces slightly higher routing overhead compared to the grid structure, making it more suitable for coverage-oriented applications.

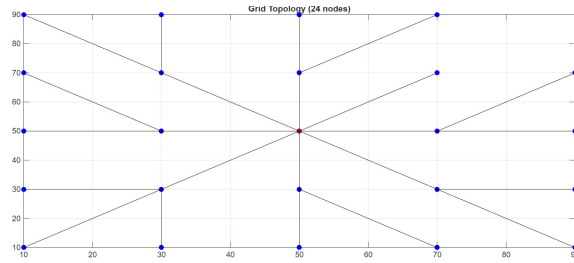


Fig. 4. Grid Topology-24 nodes

For the 24-node grid topology as shown in figure 3, the increase in node density leads to a clear transition toward multi-hop routing. The presence of multiple alternative paths enhances fault tolerance and improves throughput through parallel data transmission. However, congestion near the sink node can create a bottleneck, increasing latency. This topology demonstrates good scalability when used with structured routing protocols such as RPL.

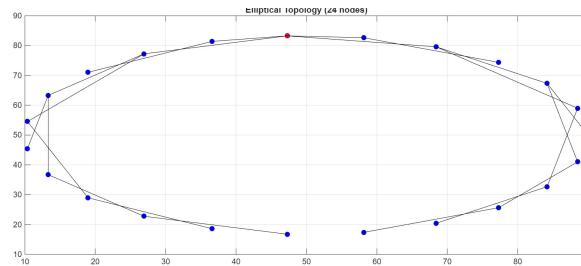


Fig. 5. Elliptical Topology-24 nodes

In the 24-node elliptical topology as shown in figure 4, the network strongly depends on multi-hop routing across perimeter nodes. Traffic is distributed along the elliptical structure, resulting in better load balancing and reduced collision probability compared to dense grid layouts. However, longer routing paths can increase end-to-end delay, making it more suitable for energy-efficient and distributed routing scenarios.

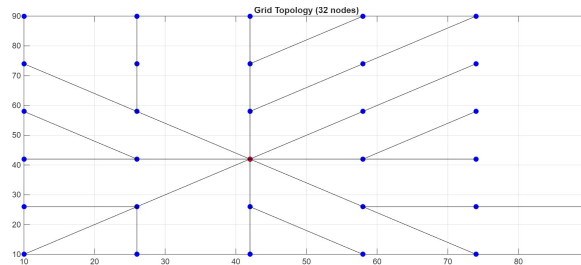


Fig. 6. Grid Topology-32 nodes

Finally, in the 32-node grid topology as shown in figure 5, the network fully operates under a multi-hop routing paradigm due to high node density. The dense connectivity graph provides multiple routing options, improving robustness and scalability. However, increased interference and congestion, especially around the sink node, lead to the hotspot problem. Efficient routing mechanisms such as RPL, load balancing, or clustering become essential to maintain network performance.

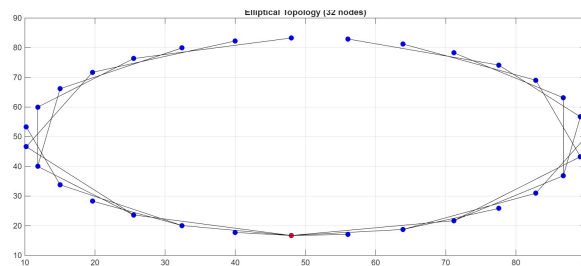


Fig. 7. Elliptical Topology-32 nodes

In the 32-node elliptical topology as shown in figure 6, the network operates entirely on a multi-hop routing mechanism, with nodes positioned along an extended elliptical boundary. Due to the increased number of nodes, inter-node distance

reduces, improving link reliability and connectivity. Data packets typically traverse along the perimeter before reaching the sink, enabling distributed traffic flow and better load balancing compared to grid structures. However, the longer curved paths can increase end-to-end delay, and routing decisions become more complex due to multiple possible paths. This topology is well-suited for energy-efficient routing, as the communication load is spread across many nodes rather than concentrated at a few points.

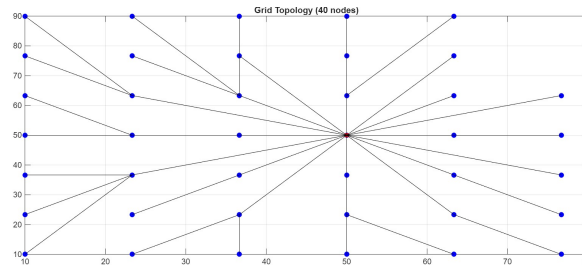


Fig. 8. Grid Topology-40 nodes

For the 40-node grid topology as shown in figure 7, the network becomes highly dense and strongly dependent on multi-hop routing. The structured grid arrangement provides high path redundancy, allowing multiple alternative routes to the sink, which improves fault tolerance and reliability. However, as the number of nodes increases, network congestion and interference also rise, particularly near the sink node, leading to the hotspot problem. This can result in increased latency and packet loss if not managed properly. Advanced routing strategies such as hierarchical routing, clustering, or RPL-based optimization are required to maintain performance and scalability in such dense deployments.

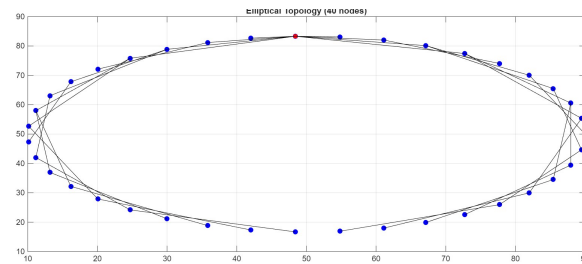


Fig. 9. Elliptical Topology-40 nodes

In the 40-node elliptical topology as shown in figure 8, the nodes form a dense elliptical structure with strong reliance on multi-hop communication across the boundary and inner paths. The increased node density enhances connectivity and reduces transmission distance, which can improve energy efficiency. Traffic is more evenly distributed compared to grid topology, resulting in effective load balancing and reduced congestion hotspots. However, the routing paths are typically longer and less direct, which can increase end-to-end delay. Additionally, the complexity of route discovery and maintenance is higher due to the irregular structure. This topology is particularly suitable for scenarios requiring balanced energy consumption and scalable distributed routing, even at the cost of slightly increased delay.

B. DISCUSSION

1. Reliability (PDR): The Grid topology maintains a higher PDR (~85%) compared to the Elliptical (~76%). In an elliptical setup, nodes on the "far ends" of the ellipse suffer from higher hop counts and weaker link qualities to the sink.
2. Scalability: As node density increases to 40, the Grid Throughput scales linearly (33.44), whereas the Elliptical throughput lags (29.68).
3. Latency: Elliptical topologies show significantly higher latency (up to 3.75s vs 2.19s in Grid). This is attributed to the "stretched" paths inherent in the geometry, forcing more intermediate hops to reach the sink.

4. CONCLUSION

This research presented a simulation-based performance evaluation of the RPL protocol in multi-hop Wireless Sensor Networks, specifically comparing the impact of Grid and Elliptical spatial distributions. Through extensive MATLAB simulations, it was demonstrated that the physical arrangement of nodes serves as a fundamental determinant of routing

efficiency, regardless of the protocol's inherent adaptivity. The Grid topology consistently outperformed the Elliptical deployment, yielding a 10-12% higher Packet Delivery Ratio (PDR) and significantly lower end-to-end latency. These improvements are attributed to the uniform neighbour density in Grid layouts, which provides a stable backbone for the Destination-Oriented Directed Acyclic Graph (DODAG) and optimizes the Expected Transmission Count (ETX) metric. In contrast, the Elliptical topology introduced geometric bottlenecks that resulted in "path stretching," where data packets were forced through elongated perimeters rather than direct Euclidean paths. Furthermore, the Grid structure proved more scalable, maintaining linear throughput growth as node density increased from 8 to 40 nodes. The study concludes that while RPL effectively manages low-power and lossy links, its performance in mission-critical IoT applications is heavily dependent on topological regularity. By minimizing hop counts and reducing parent-switching overhead, the Grid deployment ensures higher reliability and predictable latency. These findings suggest that for industrial WSN deployments, designers should prioritize structured node placement to mitigate the inherent constraints of multi-hop communication. Future work will explore the integration of mobility models and energy-aware objective functions to further enhance RPL's robustness in non-uniform environments.

References

- [1]. T. Winter *et al.*, "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks," IETF RFC 6550, Mar. 2012.
- [2]. M. Z. Hussain and Z. Hanapi, "Efficient Secure Routing Mechanisms for Low-Powered IoT Networks," *Electronics*, 2023.
- [3]. R. S. Abujassar, "Multipath Routing Protocol with Efficient Energy Consumption in IoT Applications," *EURASIP Journal on Wireless Communications*, 2024.
- [4]. D. Vyas and R. Patel, "Survey on RPL Protocol Enhancements," *IJISAE*, 2024.
- [5]. J. M. S. Silva, A. B. Junior, and L. R. M. Silva, "Evaluating WSN Devices for the RPL Protocol for Enhanced Network Performance in Industrial IoT," in *Proc. 2024 IEEE 15th International Conference on Communication Software and Networks (ICCSN)*, June 2024.
- [6]. Preeti Shakya, Alok Joshi, Pankaj Yadav, "Evaluating WSN Devices for the RPL Protocol for Enhanced Network," in *2025 International Conference on Networks and Cryptology (NETCRYPT)*.
- [7]. P. S. Rao and B. E. Reddy, "Performance Evaluation of RPL Protocol in IoT using MATLAB Environment," *Journal of Discrete Mathematical Sciences and Cryptography*, vol. 22, no. 8, pp. 1385–1395, 2019.
- [8]. O. Iova, F. Theoleyre, and T. Noel, "Exploiting multiple steps in RPL to provide better link quality," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Doha, Qatar, 2016, pp. 1–6.
- [9]. H. S. Kim, H. Kim, J. Paek, and S. Bahk, "RPL-Based Multipath Routing for Industrial IoT Applications," *IEEE Sensors Journal*, vol. 17, no. 21, pp. 7133–7143, Nov. 2017.
- [10]. P. Thubert, Ed., "Objective Function Zero for the Routing Protocol for Low-Power and Lossy Networks (RPL)," IETF RFC 6552, Mar. 2012.