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The Vocational and Applied Science Journal (VAS)

Performance Evaluation of RPL in Wireless Sensor Networks Data Collection Applications

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Abstract

Over time, wireless sensor networks (WSNs) have attracted significant research interest. These networks consist of hundreds of sensor nodes that operate without prior infrastructure, working together to monitor their physical environment. However, these nodes face limitations in memory, bandwidth, processing power, and battery life. To address connectivity and enable IPv6 functionality, the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) was introduced in 2012. Despite its widespread adoption, recent research highlights several limitations of RPL. This article offers a comprehensive evaluation of RPL, particularly in data collection applications within WSNs. It begins with an overview of RPL's key features and then compares its performance with other common routing protocols such as LOADng and LEACH across various scenarios. The article also examines RPL's behavior under different network conditions and topologies, providing valuable insights into its strengths and weaknesses. The findings aim to guide researchers and practitioners in making informed decisions and suggest future directions for improving RPL performance.

Keywords: *ETX*, LLNs, RPL, PDR, power consumption.

1. Introduction

ata, which is processed by the microcontroller, stored in memory, and transmitted to a base station via the transceiver. Since WSNs are often used in harsh environments such as battlefields or the ocean floor, replacing node batteries is extremely challenging, highlighting the importance of energy efficiency in their design and operation.

Due to the limited battery capacity of LLNs, devices must minimize energy consumption when transmitting or receiving data either between nodes or from a node to the base station. To manage communication efficiently and extend network lifespan, several protocols have been developed and standardized for these resource-constrained environments. To specifically address routing challenges in LLNs, the Internet Engineering Task Force (IETF) formed the Routing Over Low Power and Lossy Networks (ROLL) working group. In 2012, this group introduced and standardized the Routing Protocol for Low Power and Lossy Networks (RPL). Since its release, RPL has become one of the most widely recommended protocols for routing in LLNs.

Ogundile O. O. and Agboola E. (2023). Performance evaluation of RPL in wireless sensor networks data collection applications. The Vocational and *Applied Science Journal (VAS),* vol. 18, no. 1, pp. 5-10.

Despite its widespread use, RPL has significant limitations that can negatively affect network performance, as highlighted in several studies (Darabkh et al., 2022; Lamaazi and Benamar, 2020). This article provides an in-depth evaluation of RPL's effectiveness in data gathering applications within WSNs. It begins by outlining the fundamental operation of RPL in WSN environments. The study then critically compares RPL's performance across various applications with other prominent routing protocols, such as LEACH (Heinzelman et al., 2002) and LOADng (Clausen et al., 2012). Additionally, the article examines RPL's performance across different network topologies and operational scenarios, offering a comprehensive perspective on its strengths and weaknesses.

The rest of the paper is organized as follows. The RPL's operation is explained in Section 2. Section 3 examines the RPL's performance for several applications using other well-known WSN routing protocols. The RPL's performance is assessed in Section 4 under several testing setups. This section specifically describes the system model and offers a critical analysis of the outcomes. Lastly, the article is concluded in Section 5.

2. Overview of RPL Operation

In 2012, the IETF-ROLL working group introduced RPL, a distance vector routing protocol designed for low-power and lossy networks. The protocol operates under the assumption that the network contains at least one root node, which typically has greater processing power and a more reliable power supply than other nodes. RPL organizes the network into a Directed Acyclic Graph (DAG), where data is routed toward the root node through default paths (Nobakht et al., 2019). Specifically, the structure is known as a Destination-Oriented DAG (DODAG), in which all nodes forward their data to the root, commonly acting as a sink or gateway node. Fig. 1 illustrates the basic structure of a DODAG.

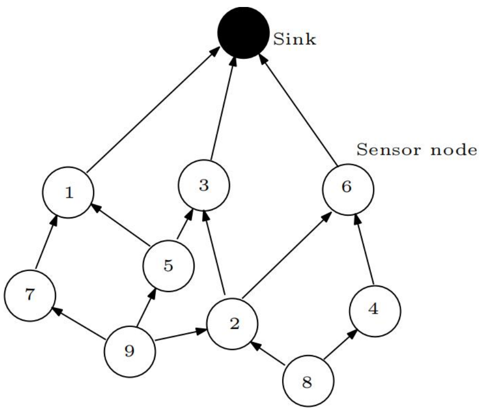


Figure 1: DODAG structure for RPL

RPL maintains and updates its routing topology using four specific types of Internet Control Message Protocol for IPv6 (ICMPv6) messages: DODAG Information Object (DIO), DODAG Information Solicitation (DIS), Destination Advertisement Object (DAO), and DAO Acknowledgement (DAO-ACK) (Al-Fuqaha et al., 2015). To initiate the formation of a new DODAG, the root node broadcasts a DIO message to its neighboring nodes. This message contains essential information such as the sender’s rank, DODAG ID, and the Objective Function (OF) used for routing decisions (Nobakht et al., 2019). The OF uses predefined metrics to calculate the rank of each neighboring node. A node’s rank, represented as an integer, indicates its relative position within the DODAG. The root node has the lowest rank, and the rank increases progressively for nodes further from the root.

There are two ways a node can react to a DIO message. The node can add the sender's DIO address to its parent list and join the DODAG. The node transmits the updated DIO message to the other nodes after calculating its rank after receiving the OF. The rank of the node needs to be greater than that of every other node in the parent list. A node can either process the DIO message to raise its ranking or ignore. Until every node has joined the DODAG architecture, the process is repeated. In order to send a message to the DODAG root, each node selects a surrounding node of lower rank as its parent node (Gaddour and Koubaa, 2012; Nobakht et al, 2019).

A node can respond to a DIO message in one of two ways. It may either add the sender’s address to its parent list and join the DODAG or choose to ignore the message. If the node decides to join, it calculates its rank using the OF, ensuring that its rank is higher than that of any node in its parent list. After determining its rank, the node broadcasts an updated DIO message to neighboring nodes. This process continues until all nodes have joined the DODAG structure. To route data toward the DODAG root, each node selects a neighboring node with a lower rank as its preferred parent (Gaddour and Koubaa, 2012; Nobakht et al., 2019).

3. RPL performance Comparison to LOADng and LEACH

RPL has been applied in a wide range of wireless networking scenarios. This section compares its performance with other commonly used routing protocols. Herberg and Clausen (2011) evaluated RPL and LOADng in the context of bidirectional traffic. Their findings showed that RPL incurred significantly higher control overhead than LOADng but was more effective in selecting optimal routes to the sink. Similarly, Vučinić et al. (2013) examined the performance of RPL and LOADng in home automation settings. Their study found that RPL outperformed LOADng in terms of memory usage, packet delay, and control overhead.

Sharma and Dixit (2019) evaluated the performance of the LEACH routing protocol in comparison to RPL, focusing on metrics such as energy consumption, throughput, packet delivery ratio (PDR), end-to-end latency, and control overhead. Their simulation results indicated that LEACH outperformed RPL across all these metrics. The authors argued that, due to the absence of a hierarchical structure in the original RPL design, all nodes are equally responsible for performing network functions such as data aggregation. This design choice contributes to increased control overhead and reduced throughput, ultimately leading to higher overall energy consumption in the network.

4. RPL Performance Evaluation

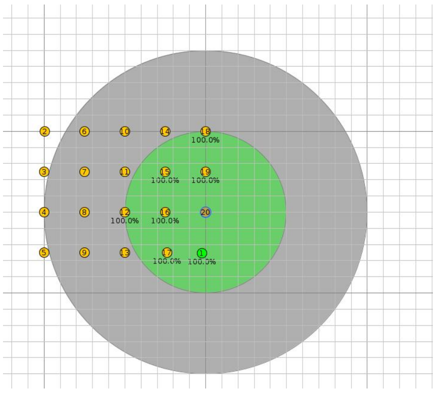
4.1 Simulation Set-up

The performance of RPL is evaluated using five key metrics: Expected Transmission Count (ETX), Hop Count (H_c), Average Power Consumption (P_c), PDR, and Routing Metric (Rt_m). These metrics are measured using COOJA, an IoT simulator designed for the Contiki operating system (OS) (Bisen and Matthew, 2018; Dunkels et al., 2004; Osterlind et al., 2006). Contiki-OS is a widely used, free platform for assessing IPv6 network performance. The simulation parameters used in this study are summarised in Table 1.

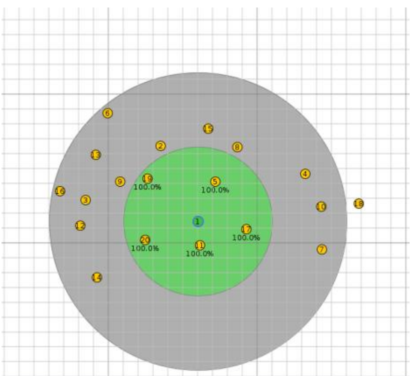
Table 1: COOJA set-up parameters

OS	Contiki 3.0
Topology	Random and Linear
Mote type	Sky mote
Radio medium	UDGM Distance loss
Transmission Range	$50m$
Number of motes	20, 40 and 60
Interference Range	$100m$
Transmission and	100%
Reception Ratio	RPL
Network Layer	UDP
Transport Layer	$30min$
Simulation Time	

In Table 1, the COOJA simulator assumes the unit disc graph model distance Loss (UDGM - Distance Loss) as its radio medium. In the UDGM, every nodes has two ranges for interference and transmission, which are represented as a disk Nobakht et al, 2019. This interference and transmission ranges are set to 100m and 50m respectively. The default transmission and reception ratio of 100% is assumed. Two underlying network topologies (linear and random) were used in the simulation set-up. As a result, the RPL's performance for these network topologies was recorded. The random and linear network topologies for 20 nodes in COOJA are shown in Fig. 2. Additionally, in increments of 20, the number of mote sky nodes was changed from 20 to 60. There is only one sink in each setup. For instance, there are 19 client nodes and a sink in a 20 node setup.



(a) Linear



(b) Random

Figure 2: 20 nodes Network topologies in COOJA

4.2. Performance Metrics

As previously stated, the RPL's performance is assessed using five distinct metrics: ETX, P_c, H_c, Rt_m, and PDR.

1. ETX : The ETX is the number of transmissions required for a packet to be acknowledged and transferred successfully .

2. H_c : The number of receiving and transmitting nodes between the source node and final destination nodes is called the H_c.

3. P_c : An estimate of the average power consumed by the network's nodes during packet transmission is defined by the P_c. It is mathematically represented as:

$$P_c = \frac{\sum_1^n \left(P_{cpu}\right)_n + (P_{LPM})_n + (P_l)_n + (P_t)_n}{n}, \quad (1)$$

where P_{LPM} is the low mode power , P_t is the transmission power mode, P_{cpu} is the power of the central processing unit, P_l is the listening power mode, and n is the total number of nodes

4. PDR : The PDR is the ratio of the total received packets (R_p) to the total transmitted packet (T_p). It is given as:

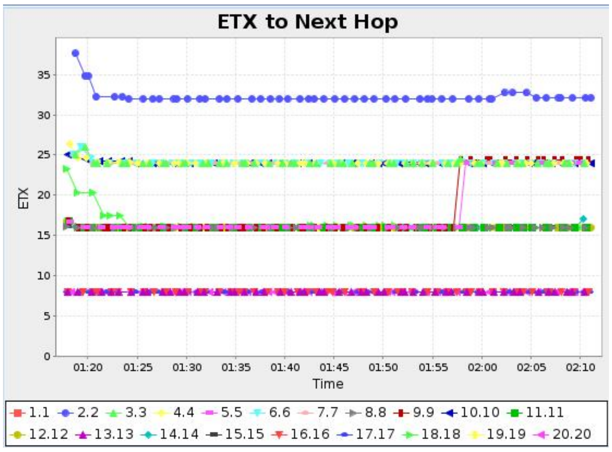
$$PDR = \frac{\sum R_p}{\sum T_p}. \quad (2)$$

5. Rt_m : The For a given route, the Rt_m calculates the path cost. It calculates this path cost by considering the total number of hops, packet loss, speed, latency, and other factors.

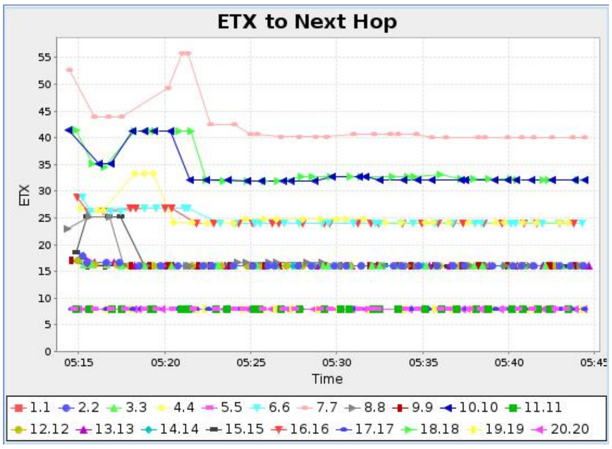
4.3. Results and Discussion

Fig. 3 illustrates the ETX performance of RPL across 20 nodes arranged in different network topologies. Essentially, the graphs depict the ETX value for each node to its next hop or closest neighbor used to forward packets to the sink. As shown in Fig. 3, Node 2 (labeled as 2.2) exhibits the highest ETX . This outcome is expected, as shown in the node placement graph in Fig. 2a, where Node 2 is the farthest from the sink. Similarly, in Fig. 2b, Node 7 (labeled 7.7) is the most distant from the sink and correspondingly has the highest ETX in Fig. 3b. It is reasonable to assume that these nodes experience the longest end-to-end packet delays when sending data to the sink.

Fig. 4 further illustrates each node's performance relative to its distance from the sink. As expected, the transmission cost increases with distance. In Fig. 4a, Node 2 requires the most effort to transmit packets to the sink, followed closely by Nodes 3, 4, 6, 7, and 10. Likewise, in Fig. 4b, Node 7 has the highest transmission demand, with Nodes 10 and 18 following.

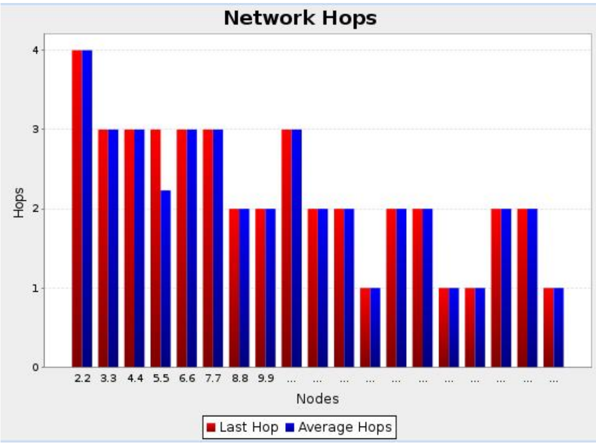


(a) Linear

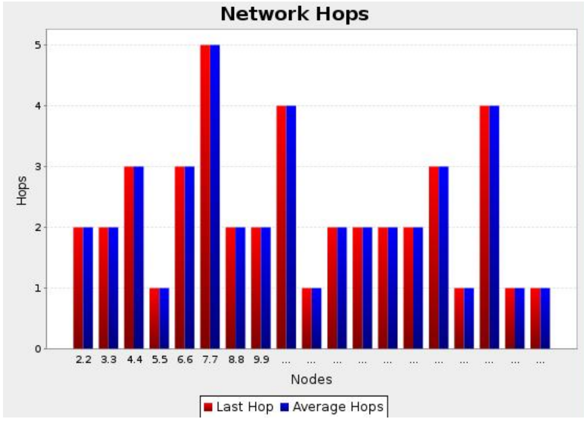


(b) Random

Figure 3: *ETX* for linear and random topologies (20 nodes)



(a) Linear



(b) Random

Figure 4: H_c for linear and random topologies (20 nodes)

Importantly, RPL's performance was evaluated across various underlying network topologies and scalability levels, focusing on key metrics such as PDR and others. Fig. 5 presents the RPL's performance for different topologies and varying numbers of nodes. First, the results show a significant decline in PDR as the network size increases, indicating that RPL's efficiency deteriorates rapidly in large-scale WSNs with more than 100 sensor nodes deployed across the sensing area. Second, despite the growing number of nodes, the linear topology consistently achieves slightly better PDR performance compared to the random topology.

Fig. 5 illustrates the power consumption throughout the simulation. As expected, power usage increases with the size of the network. Additionally, the linear topology consumes slightly more power than the random network configuration. Fig. 7 highlights the power consumption of individual nodes during transmission rounds. For example, Node 2 uses the least power since it is rarely used as a relay to forward packets to the sink (Fig. 7a). In contrast, nodes closer to the sink such as Nodes 20, 16, and 17 consume more power because they handle more traffic by routing packets from other nodes. Similarly, in both linear and random topologies, nodes like 19, 5, 20, 11, and 17 use more energy due to their proximity to the sink. Conversely, nodes 7 and 18, which are seldom used as relay points, consume less power. This routing pattern can lead to the energy-hole problem (Ogundile and Alfa, 2017), where nodes near the sink exhaust their batteries faster due to constant packet forwarding. This premature energy depletion may cause early network partitioning, preventing nodes farther from the sink from communicating effectively.

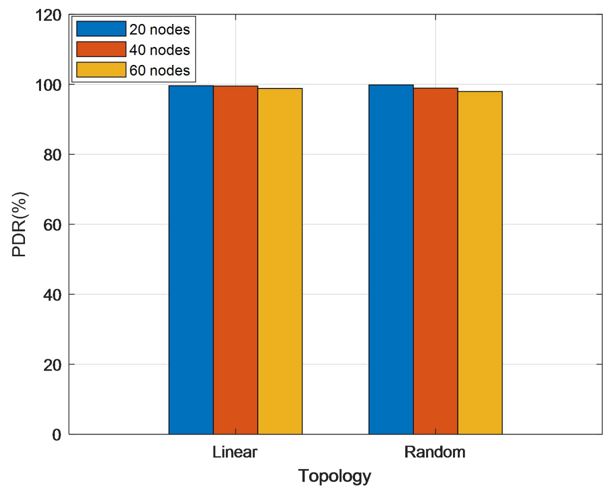


Figure 5: PDR performance comparison for network scalability and topologies

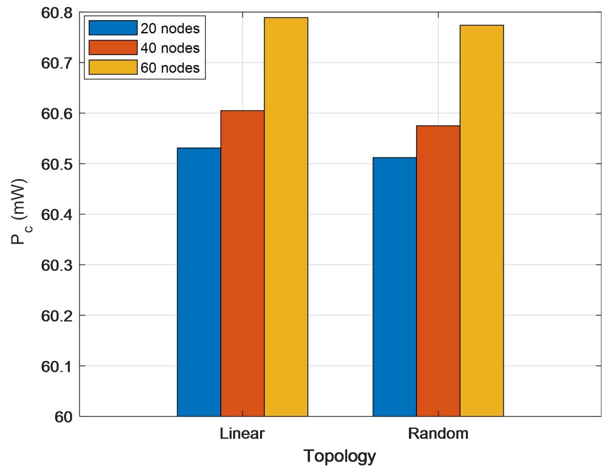
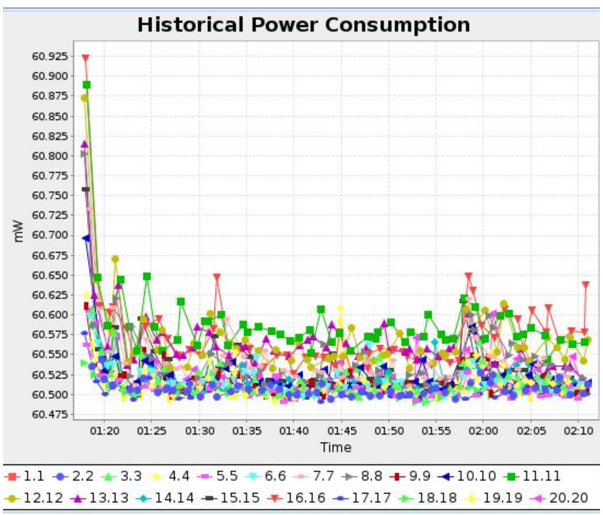
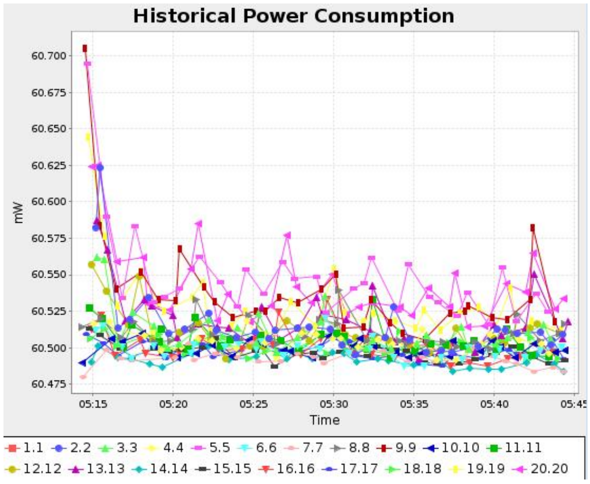


Figure 6: P_c performance comparison for network scalability and topology



(a) Linear

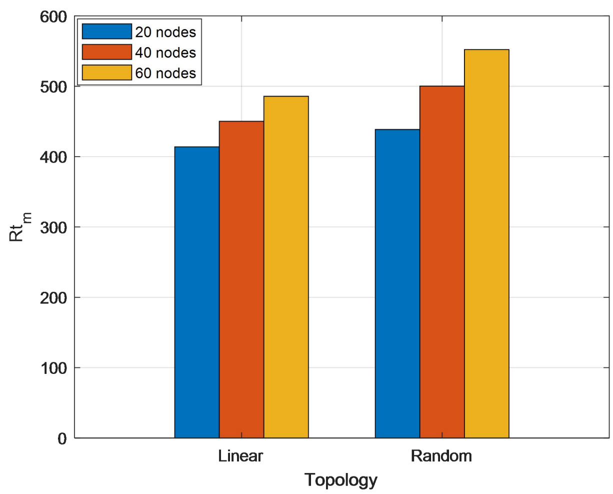


(b) Random

Figure 7: Power consumption by each node in the network

Besides, Fig. 8 shows the average path cost performance for both random and linear network topologies. As the network size increases, the average path cost rises for both topologies. However, across all network sizes, the linear topology consistently outperforms the random topology in terms of average path cost.

Figure 8: Rt_m comparison for network scalability and topologies



5. Conclusion

This article evaluated the performance of the RPL protocol in data gathering applications within WSNs, focusing on the impact of network topology and scalability. The results showed that a linear topology outperforms a random topology in several specific performance metrics. However, the random topology consumes less overall network power compared to the linear one. As network size increases, RPL performance declines across all evaluated parameters, indicating that RPL may not be well-suited for large-scale WSN data collection applications. Future research should focus on enhancing RPL's scalability and efficiency in larger networks. Additionally, the protocol's suitability for underwater WSNs warrants further investigation.

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