Implementation of RPL Protocol Modifications to Improve IoT Communication Performance

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Abstract: In IoT-based wireless sensor networks, various types of data are transmitted as various devices are utilized. In addition, the data communicated increases according to the number of deployed nodes. However, since the battery of IoT nodes is limited, a routing method that can communicate while minimizing energy consumption is essential. In order to build a mesh network in such a low-power IoT sensor network environment, the Routing Protocol for Low-Power and Lossy Networks (RPL) was developed. Using the RPL protocol, it is possible to prevent dead zones where wireless network communication is not possible and control a large area at once. RPL relies on an objective function to determine optimal routing paths, with each function employing different metrics to enhance network efficiency. This study aims to improve RPL's performance in dense IoT-WSN by introducing two modified objective functions. In the paper, two versions of the protocol are proposed. The first MRPL1 is designed considering the number of neighboring nodes and the energy of IoT devices in the network. The second MRPL2 is designed considering neighboring nodes and child nodes. The protocol uses Expected Transmission Count (ETX) as a performance evaluation criterion. Simulation results demonstrate that MRPL1 achieves a 92% improvement in energy efficiency compared to standard RPL protocol. Similarly, MRPL2 improves energy savings by 15% over RPL.

Key-Words: IoT-WSN, IPv6, Network Routing, Objective function, Protocol

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1 Introduction

The Internet of Things(IoT) encompasses a network of diverse devices interconnected through the internet, enabling seamless data exchange without human intervention. Devices assigned IP addresses can autonomously collect, process, and transmit data, facilitating a wide range of applications, including healthcare, wearable technology, traffic monitoring, and precision agriculture. As IoT continues to expand, efficient data communication and network management become increasingly crucial, [1], [2], [3], [4], [5].

Wireless Sensor Networks(WSNs) form an integral part of IoT ecosystems, consisting of numerous sensor nodes deployed to monitor environmental and physical conditions. These sensor nodes are compact, cost-effective devices with constrained resources, including limited sensing, data processing, wireless communication, and energy capabilities. Given these limitations, designing optimized routing protocols for IoT-WSNs has become a key research focus to enhance network efficiency, reduce energy consumption, and ensure reliable data transmission. In this study, we investigated routing protocols applicable to IoT wireless sensor networks. In particular, we conducted research to provide scalability in resource-constrained environments such as IoT device batteries, [6], [7], [8], [9], [10].

IETF ROLL has published the RPL standard, a routing protocol applicable to low-power loss networks, through various researches. RPL supports different link layers and can be used in home and industrial environments. The connection between nodes by RPL is formed by multiple sets of root devices through multi-hop paths. They perform the role of data collection and adjustment for network environment changes. Given the limited energy and computational resources of sensor nodes, extensive research has focused on optimizing RPL to enhance energy efficiency and network longevity, [11], [12], [13].

Several studies have explored modifications to improve RPL's performance. One such approach, the Energy-Efficient and Reliable RP(ER-RPL), combines proactive and reactive routing to enable reliable peer-to-peer communication without compromising efficiency. Unlike traditional routing methods, ER-RPL utilizes a subset of strategically placed nodes to optimize route discovery while employing ETX as a link quality metric. Simulation results using NS-3 with 100 nodes in a 180 $\times$ 180 m^2 network demonstrated that ER-RPL improved PDR by approximately 145% and reduced energy consumption by over 58% compared to standard RPL, [14], [15], [16].

Another enhancement, the Quality of Service Objective Function (OFQS), introduces a multi-objective metric that integrates average time delay, remaining node energy, and ETX to refine parent selection, [17], [18]. Evaluations conducted using 67 nodes in the Cooja simulator revealed that OFQS achieved a PDR improvement of 92%, surpassing the 86% performance of Objective Function Zero(OF0) and Minimum-Rank with Hysteresis Objective Function(MRHOF). Experiments have shown that the RPL protocol works better in resource-limited environments such as IoT-WSN. The reason is that when routing in the network, various factors can be considered and stable packets can be transmitted compared to existing network protocols.

Previously, many studies have been conducted for optimized routing in an environment to which the proposed number of nodes is applied. Recently, research on routing and energy saving in a high-density network environment has been conducted. One study conducted an experiment on the assumption that there are hundreds of IoT nodes using NS-3 network simulation. In particular, the experiment analyzed the performance of OF0 according to the node placement. When OF0 according to the experimental results was used, performance improvement by about 7% compared to the existing objective function. It was also possible to save energy in consideration of routing paths in the network, but the selection of the objective function was also shown to be important.

In this paper, we propose a plan to improve the overall performance of the sensor network. In particular, it is a protocol that considers the surrounding situation of the node when routing nodes in the network. The proposed protocol modified the problems of the existing RPL protocol(MRPL1). Second is the modified RPL 2 (MRPL2) that thinks value of node and path. The experiments were conducted in three different environments (100$\times$100 m^2, 150$\times$150 m^2, and 200$\times$200 m^2) with varying node densities. The experimental results showed that proposed methods proof better efficiency than the standard RPL when comparing energy and PDR. In addition, more accurate changes could be confirmed when testing while changing the size of the experimental environment.

Several studies have considered various factors to select parent nodes in IoT node environments. For parent selection, the number of parent nodes and the number of parent nodes with the maximum energy were considered. In addition, the number of parents with the minimum maintenance energy was measured and used. Simulations showed that Maximum number of parent on Remaining Energy(MRE) reduced energy consumption by up to 32% in small networks compared to traditional RPL while improving energy distribution and parent switching efficiency in different network densities.

Furthermore, a Multipath RPL(MP-RPL) approach was introduced to enhance video traffic delivery in IoMT applications by leveraging multiparent RPL features. Experiments with 12 nodes in a 150$\times$150 m^2 simulation area demonstrated that MP-RPL, combined with an ETX-based objective function, significantly improved video traffic distribution, reducing network congestion and average delay compared to single-path RPL, while maintaining similar energy consumption levels. Experimental results emphasize the importance of routing methods in high-density network environments. Depending on the routing method, the performance of the RPL protocol may vary.

2 Related Works

Recently, a lot of research on the RPL protocol has been conducted to improve network performance in the IoT environment, [19], [20], [21], [22]. The initial RPL protocol was proposed for the IoT-based sensor network. In particular, it was developed to solve errors that may occur when transmitting limited batteries and acquired environmental data of IoT nodes. In 2010, environmental changes were reflected with the development of IoT devices. In the RPL protocol, the estimated number of transmissions (ETX) was introduced as an important indicator for performance measurement. This indicator indicates how many transmissions are required to successfully transmit packets at a single node. In a network using the RPL protocol, routing is performed using ETX information. In addition, when routing, the number of nodes in the network is considered. Using such various information, routing is performed to reduce the energy of the network. Recently, in order to improve the existing routing method, further research is being conducted that considers various factors.

Several studies have explored enhancements to RPL by leveraging ETX as a link metric. Certain studies have proposed a multipath method when transmitting data. In this method, when transmitting data from one node to the base station, all data is now transmitted through multiple paths without majoring in one path. In this study, the ETX value and the number of hops between nodes were used when establishing routing paths. It was verified that the network load decreased when using such a multipath system when transmitting a large amount of data. As a result of the experiment, it was confirmed that the multipath method works normally in a general network environment and an IoT sensor network environment. In addition, it was verified that data is transmitted without loss in a dense environment of nodes. Through accurate data transmission, the effect of saving the energy of the node could be obtained, [23], [24].

Further advancements in RPL optimization include enhancements to control message dissemination and network self-configuration. One study proposed a method to increase the efficiency of packets transmitted, especially packets transmitted from the root node, [25]. Their study focused on reducing redundant control message overhead, thereby improving overall network efficiency and reducing unnecessary energy expenditure. Efficient control message propagation is critical in LLNs, as excessive signaling can deplete node resources and contribute to network congestion.

Research was conducted to improve the performance and optimization of the RPL protocol. Message management for network maintenance and control was studied to improve the performance of the protocol, [25]. The study suggested a method to deliver messages efficiently when brocasting messages from the top node of the network to child nodes. When sending the entire message, there is a problem that duplicate messages may continue to occur after receiving the message from the lower node. The study proposed a method to reduce duplicate messages at lower nodes. The proposed message transmission method can reduce the network overhead. When there are nodes with limited energy such as IoT, duplicate messages cause energy to be depleted.

As an important study in relation to the protocol, the use of multiple channels for connections between nodes in RPL-based networks has been studied, [26], [27]. Their research focused on detecting connectivity issues and optimizing the channel scanning process to enable self-configuration and improve data transmission reliability. Multi-channel routing strategies have the potential to alleviate interference and enhance throughput, particularly in large-scale IoT deployments. Despite these improvements, challenges such as channel selection accuracy and dynamic adaptation to changing network conditions remain open areas of research.

While these studies have contributed valuable insights into RPL enhancements, several unresolved issues persist. Current research primarily focuses on refining routing metrics, optimizing control message exchanges, and improving load balancing strategies. However, security vulnerabilities of networks using the RPL protocol and routing in networks using various IoT nodes require further research. In addition, additional research is needed on methods to provide network reliability and energy efficiency. The various studies presented above are essential for improving the reliability and performance of RPL. Through such continuous research, the future IoT environment will improve in a better direction.

2.1 Routing Protocol for Low-Power and Lossy Networks(RPL)

The RPL protocol was proposed to solve the energy limitation problem and data loss problem of nodes in IoT sensor networks. The RPL protocol follows the IEEE 802.15.4 standard and utilizes a proactive distance vector routing protocol, enabling efficient data transmission in resource-limited environments. Similar to other sensor networks, RPL supports three basic communication models(many-to-one communication, one-to-one communication, multi-hop communication). Based on these communication models, flexible data exchange between network nodes is possible. In order to maintain network topology in the RPL protocol, Destination-Oriented Directed Acyclic Graph (DODAG) is applied. DODGA prevents routing loops by maintaining an acyclic structure. The root node, known as the DODAG root, serves as the central destination for data collection and dissemination. RPL constructs and manages its network through various control messages that facilitate topology, formation and route maintenance, [28], [29], [30].

The DODAG Information Object (DIO) message can be used for a variety of purposes. DIO messages can be used to discover RPL network instances, configure network parameters, and select a parent node for routing. The DODAG Information Request (DIS) message is used to request a DIO message from a neighboring node. The requested information is used to search the network and perform maintenance. The Destination Advertisement Object (DAO) message is sent to the parent node to join the network. Sensor nodes that receive the DIO message for the upward path select a parent node and record their address information in the DAO message and send it to the parent node. The parent node that receives the child node's DAO message accumulates its address information and sends it to the parent node, [31], [32].

By leveraging these control messages, RPL dynamically adapts to changing network conditions, optimizing routing decisions and ensuring efficient communication in low-power and lossy network environments. However, despite its advantages, RPL faces challenges in link quality assessment, energy efficiency, and scalability, necessitating further research to enhance its performance in large-scale IoT deployments.

2.1.1 Operation of RPL

In RPL, each node forms an upward path (MultiPoint-to-Point) to transmit data information collected from sensors to the sink node. Considering the LLNs characteristics of IoT networks, DODAG is formed in a proactive manner. The sink node floods the entire network with DIO messages using routing metric values to form DODAG according to the application required in the IoT network, and each sensor node receives the transmitted DIO messages through multiple paths.

Each sensor node selects the node with the lowest routing metric value as the parent node and selects other upper nodes as reserve parent nodes. The DAG formation process is repeated to form a DODAG and to enable packets to be transmitted to the sink node. Each sensor node that forms the DODAG transmits collected data packets to the sink node through the parent node.

Due to the mobility of sensor nodes, which is a characteristic of IoT networks, and the loss of sensor nodes due to battery exhaustion, there are frequent cases where data packets cannot be transmitted. If the network topology changes due to the above problems, there are cases where data packets detected within the IoT network cannot be transmitted to the sink node. In this case, in the RPL standard, when the loss of the parent node, which is the upper node, is detected, the subordinate node selects a spare parent node selected during the DAG formation process as the parent node and transmits the data packets to the sink node. A lost node occurs in the upward path, a spare parent node is selected and recovered.

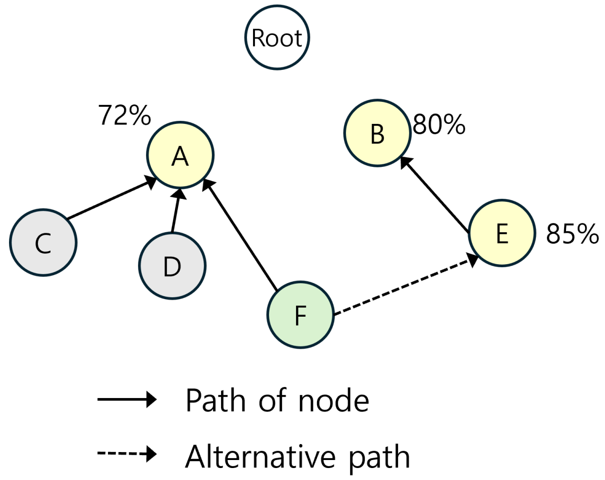

Figure 1: Illustration of OF0 Preferred Parent Selection Process

2.1.2 Objective Function of RPL

In the RPL protocol, MRHOF and OF0 can be used as objects and functions. Since the development of the RPL protocol, researchers have developed additional objective functions to improve the performance of RPL by considering various networks. Objective Function Zero selects a parent node only by considering the number of hops to the root node for fast operation. It does not consider network congestion or energy. While Objective Function Zero is effective in small-scale networks, its limitations become apparent in medium- and high-density deployments. When multiple nodes select the same parent based on hop count alone, this can lead to traffic congestion and excessive energy depletion at the selected parent node. Additionally, OF0 fails to account for energy-aware routing, which can result in the premature exhaustion of heavily utilized nodes, reducing overall network lifespan. Fig. 1 show the example of OF0 preferred parent selection process.

For example, as shown in Fig. 1, two nodes A and B are configured as children of the root node. Nodes C and D select node A, which is right above it, as their parent node. Also, node E selects node B as its parent node. At this time, a new node F can select node A or node E to join the network. Node A has the smallest number of hops when transmitting packets to the root. Node E has more energy than node A, but it has a larger number of hops compared to moving to node A, so it selects node A as the path in OF0. This imbalance in parent selection increases the burden on node A, accelerating its energy depletion and potentially disrupting network stability. Consequently, more advanced objective functions are needed to optimize parent selection by incorporating energy awareness and load-balancing mechanisms.

3 Proposed Method

3.1 Modified RPL protocol 1 (MRPL1)

In this paper, we propose a modified RPL protocol 1 (MRPL1) to improve the performance of the existing RPL. In the proposed method, routing is performed by considering the energy of the node, the number of adjacent nodes, and children. The primary objective of MRPL1 is to balance the network load by evenly distributing nodes, thereby preventing excessive energy depletion in heavily utilized nodes. MRPL1 maintains the core structure of RPL. However, it applies an improved parent selection method to increase the efficiency of routing in the network.

The DODAG root node transmits a DIO message to all neighboring nodes. A node that receives a DIO message transmitted to the network selects the node that sent the message as its parent. Then, it creates a DAO message using the received message information and transmits it to the parent node. The parent node receives the DAO message and the child that sent the message transmits a response message. In this way, each node in the network can expand the network configuration by sending DIO messages to neighboring nodes.

There are two cases to consider when a node in the network receives a DIO message. When the message is received, if it is determined that it is at the same stage as the sending node, the message is not used and deleted. Conversely, when the message is received, if it is determined that it is above the sending node, the mesh is accepted and the node is determined to be above. In both cases, the location of the node is determined when the DOI is first received. In particular, the mesh determines the sending node as the upper node. When it is determined in this way, the lower node determines that there is an upper node and updates the information in its node list.

When a node in the network receives multiple DIO messages and has multiple potential parents, the cost of the current parent node and the potential parent node are compared using the formula presented in the paper. After performing the comparison, if the cost of the potential potential parent is lower, the potential parent is selected as the new parent. Then, the previous parent is deleted from the node's parent list. The selected parent is then informed via a DAO message, after which the parent updates its child list accordingly.

By dynamically adjusting parent selection based on energy level, network density, and node distribution, MRPL1 enhances routing efficiency, reduces node congestion, and prolongs network lifespan while maintaining compatibility with RPL's fundamental structure.

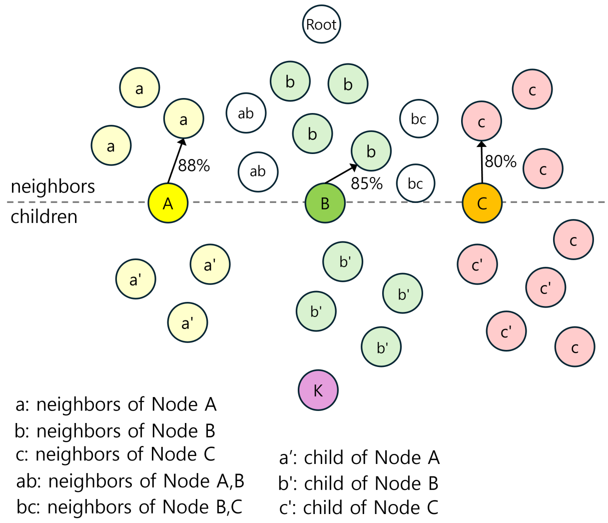

Figure 2: Example of the nodes configuration

$$COST1 = wp0\frac{Re}{Ie} + wp1\frac{N}{C+1} \quad (1)$$

In the proposed model, wp0 and wp1 constitute parameters of weight, which were adjusted to achieve optimal performance. Cost calculation utilizes information available at a node. The formula uses the initial energy of the node (Ie), the remaining energy (Re), the number of neighbors of the node (N), and the number of child nodes (C). To ensure proper metric evaluation for leaf nodes, 1 was added to Equation (1), preventing the numerator from becoming zero in fractional calculations. This adjustment allows for a more accurate representation of network conditions while maintaining consistency across different node types. As with typical network communication, nodes within the root's transmission range are directly connected to the root without having to select a parent. However, for nodes located within the network but not at the edge, a selection process is required to determine the most suitable parent.

For example, assume that there is a new node D in a network currently consisting of nodes A, B, and C. Each of these potential parent nodes has distinct network attributes: Node A has an energy level of 88%, three neighbors, and three child nodes; Node B has 88% energy, eight neighbors, and an four child nodes; Node C also has 80% energy, but with five neighbors and five children. Fig. 2 shows the node configuration of the example.

To make an informed selection, node D computes the cost value for all candidate parents using Equation (1). Through the above calculation, the node with the highest cost is selected as the parent node. The selected parent node takes into account the energy situation and efficient network topology.

In this case, node A is selected as node D's preferred parent, as it provides the most favorable balance between energy availability and network load. This selection process ensures equitable parent distribution, reducing congestion and preventing excessive energy depletion in high-density IoT networks.

$$COST1\ of\ Node\ A = 10 \times \frac{88}{100} + 1 \times \frac{3}{3+1} \quad (2)$$

$$COST1\ of\ Node\ B = 10 \times \frac{85}{100} + 1 \times \frac{4}{4+1} \quad (3)$$

$$COST1\ of\ Node\ C = 10 \times \frac{80}{100} + 1 \times \frac{3}{5+1} \quad (4)$$

3.2 Modified RPL protocol 2 (MRPL2)

The MRPL2 protocol integrates both node and path metrics to optimize routing efficiency. In the proposed MRPL2 method, unlike MRPL1, the number of neighbors of a node and EXT are used to calculate the cost. The operational structure of MRPL2 closely follows that of MRPL1, with additional refinements in parent selection criteria.

When a node inside the network receives a DIO message and joins the MRPL2-based network, it calculates the value according to equations (5) and (6).

Then, the Cost2 value is calculated using Equation (7). The upper node of the current node is selected using the value calculated above. Using Equation (7), the values of the nodes are calculated first, and the smallest value is selected among them. The node selected in this way is determined as the upper node. Since this equation considers the path of the node, the energy used in the network can be reduced. In addition, the load on the entire network can be reduced by reducing the path. The equation proposed in this paper considers the value of the node and the value of the path. In Equation (5), branches of the node are assigned in consideration of the neighbor and child of the node. In Equation (6), ETX is considered.

The weight values used in the equation were determined through a number of experiments for wp0 and wp1. When routing in the network using this value, there was no bias and the best performance was achieved. Through this, the stability of the network and the optimal link could be established.

$$Node\ value = wp0 \times \frac{C+1}{N} \quad (5)$$

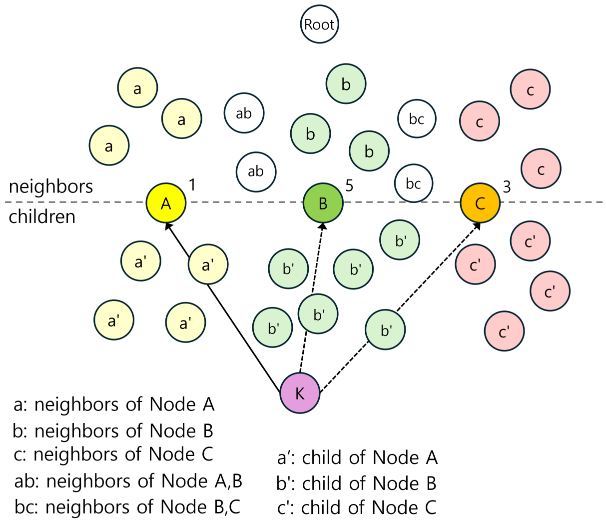

Figure 3: Parent node selection method using MRPL2

$$Path\ value = wp1 \times ETX \quad (6)$$

$$COST2 = Node\ value + Path\ value \quad (7)$$

Fig. 3 shows the MPRL2 algorithm proposed in this paper. In this algorithm, both the situation and path of the adjacent node are considered in order to select the optimal parent at the current location. It is assumed that a new node K enters the network when the current network is configured. Node K is calculated using Equation (7) considering the surrounding interaction in order to select a parent. When the values of A, B, and C in the network are calculated, A is selected as a node with a minimum value because A has a minimum path value of 1. According to the calculated value, node A is determined as the parent node of K. In this way, the load on the network can be reduced by considering the situation and path situation of the neighboring nodes of the node. As a result, total energy can be saved and the efficiency of the data transmission link can be provided.

4 Results

In order to verify the algorithm proposed in this paper, the experiment was conducted using network simulation. The experiment was continued by changing the number of nodes used in a certain area. In the experiment, a minimum of 100 to a maximum of 300 nodes were applied and compared. Each node was initially set to a state with 2000mAh and the experiment was conducted. This value was selected as the average value of nodes widely used in IoT-WSN.

In recent IoT-WSN environment experiments, simulators such as packet tracer, GNS3, and COOJA have been widely used. In this paper, the COOJA simulator was selected and used for the experiment. The COOJA simulator is distributed and configured to be easy to use like the Contiki open-source operating system. This operating system is manufactured to operate efficiently even on low-spec hardware. For this reason, the RPL protocol used in this paper can be applied and test experiments are possible.

In this paper, we propose two versions that can improve the performance by improving the existing RPL protocol. In order to verify the proposed method, the RPL protocol and the modified bourbon were compared and tested. In the experiment, several comparison factors were selected to evaluate the performance of the protocol. The experiment was conducted by fixing the size of the experimental environment and changing the number of network nodes from 100 to 300. The packet transmission amount, node energy consumption, and average delay time were measured according to the node change. Based on the experimental results, it was found that the improvement protocol proposed in this paper has superior performance than the existing RPL protocol. It has been proved that energy can be saved even when the number of nodes increases. This is because when setting up a network path, the value of the path is considered.

Fig. 4 shows the results of the experiment while fixing the size of the IoT network experiment environment and changing the number of nodes. In the experiment, the evaluation was conducted by applying the existing RPL protocol and the two improved protocols proposed in the paper. The evaluation item is the energy use rate according to the increase in the number of nodes. The existing RPL protocol showed that as the number of nodes increases, the energy of the node decreases rapidly as the number of packets moves across nodes. However, as for the method of designing in this paper, various items were considered to perform routing to transmit packets. In particular, the current situation of neighboring nodes and the value of the path were considered. Accordingly, even if the number of nodes in the experimental environment increased, the energy of the node could be saved.

When selecting a parent node in a network, if only one value is used for calculation, the number of nodes that can be selected will be reduced. This will cause the packet transmission path to become longer and increase energy consumption. This effect becomes more pronounced as the network size and node density increase. The results in Fig. 4 indicate that MRPL1 achieved a 94% improvement over RPL, while MRPL2 also demonstrated a 96% energy efficiency gain over RPL. The integration of ETX alongside neighbor and child node considerations in MRPL2 further enhances network performance by reducing retransmissions, thereby minimizing overall energy consumption, particularly in larger network deployments.

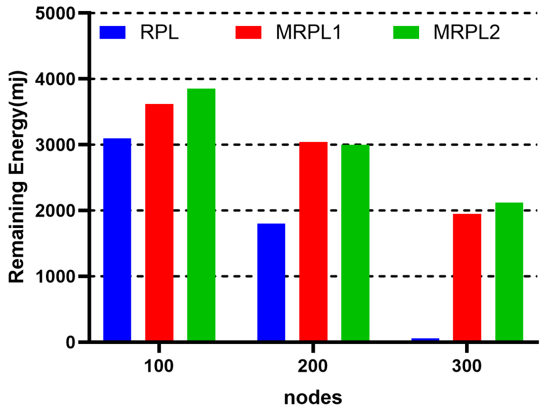

Figure 4: Remaining energy results according to number of nodes

Fig. 5 presents the average time delay for MRPL1, MRPL2, and RPL under varying network conditions. The results indicate that node density and the number of dead nodes significantly impact processing time, as higher node failure rates increase communication overhead and processing delays. For MRPL1, the average delay was 0.1342 seconds in a $25 \times 25\ m^2$ area with 100 nodes, increasing to 0.27 seconds with 200 nodes and further rising to 3.78 seconds with 300 nodes. A similar trend was observed across all evaluated protocols. The use of three selection metrics in MRPL1 and MRPL2 contributed to better load distribution by increasing the number of eligible parent nodes. This prevented network congestion at specific nodes, reducing excessive message queuing and overall waiting time. These findings highlight the advantages of multi-metric parent selection in mitigating network delays and enhancing communication efficiency in dense IoT-WSN deployments.

Fig. 6 shows the measured PDR ratio as the number of nodes increases in a space of a certain size. As node failures increase, the PDR declines, affecting overall network performance. In scenarios with 100 nodes and densities of 0.17, 0.05, and 0.04, all evaluated protocols exhibited similar performance. However, at lower densities, specifically 0.004 and 0.0073, MRPL1 and MRPL2 outperformed RPL, maintaining a higher PDR. This improvement is attributed to fewer node failures in MRPL1 and MRPL2, whereas RPL experienced higher node

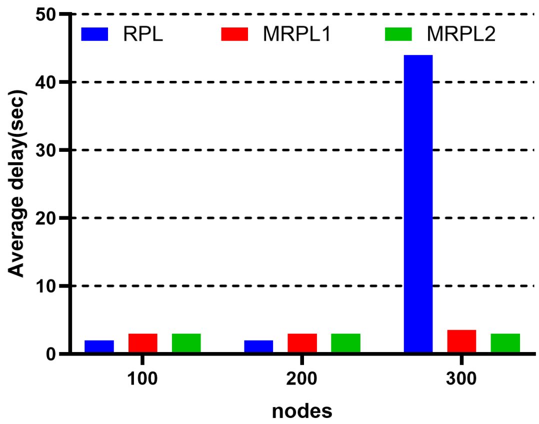

Figure 5: Number of Packet Retransmissions

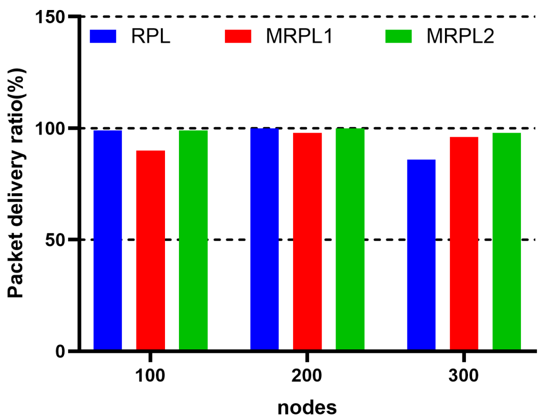

Figure 6: Relationship between Packet Delivery Ratio(PDR)

loss, leading to reduced data transmission reliability. Experimental results show that parent node selection is important in wireless sensor network environments. Parent node selection is the basis for ensuring efficient data transmission and providing network stability in LLNs environments.

Fig. 7 illustrates shows the change in throughput as the number of nodes in the experimental space increases. As the number of nodes increases in a wireless sensor network environment, the data processing speed also increases. However, as the number of nodes decreases, the data transmission speed slows down. Additionally, in an experimental environment, it was shown that as the number of nodes that are not functioning due to energy depletion increases, throughput in large-scale networks decreases. In contrast, MRPL1 and MRPL2 maintained higher throughput levels, particularly in networks with 200 and 300 nodes. The

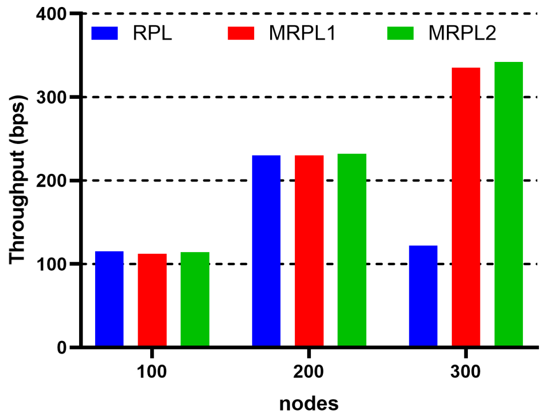

Figure 7: Throughput as the number of nodes increases

improved performance of MRPL1 and MRPL2 can be attributed to better load distribution and reduced packet loss, ensuring more stable data transmission and efficient utilization of network resources.

5 Conclusion

In this study, we propose a method to improve the network performance in LLNs environments. In particular, we propose two protocols by modifying the existing RPL protocol. MRPL1 selects preferred parents based on energy levels, number of neighbors, and child nodes, while MRPL2 extends this approach by incorporating ETX to enhance link reliability. Both protocols were implemented and evaluated using the simulation. To verify the method proposed in the paper, simulation experiments were performed. The experimental results confirmed that MRPL1 and MRPL2 proposed in the paper performed better than the existing RPL in various network environments. In high and medium density networks, MRPL1 achieved superior energy efficiency compared to RPL, whereas MRPL2 performed more effectively in low-density scenarios. Specifically, MRPL1 reduced energy consumption by 95% over RPL. Meanwhile, MRPL2 showed 98% performance improvement over RPL when tested in the same size space with the same number of nodes. These findings confirm that the proposed protocols enhance energy efficiency, improve network stability, and optimize routing performance in IoT-based LLNs.

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