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Advancing Healthcare Networks: Optimizing Multi-Objective RPL for Diverse Traffic in Low-Power, Lossy Environments

Abstract: RPL: Powering modern healthcare IoT Networks. The Routing Protocol for Low Power and Lossy Networks(RPL) is a protocol specifically designed for routing in networks characterized by low power and lossy connections built on IPv6. It is specifically designed for the growing use of Instantaneous IoT (Internet of Things) applications. These networks cater to the specialized requirements of Low Power (resource-constrained) and Lossy Networks(unstable networks), also known as LLNs, where routing data smoothly and prioritizing traffic types are the significant challenges. Studies have shown that standard RPL, which makes use of a set of routing rules, struggles to provide the level of performance that many IoT applications in modern-day healthcare demand. This limits RPL's potential in scenarios where we have a mix of data traffic, which is very common in healthcare settings. To handle the diverse data traffic found in healthcare settings, our method involves distributing several instances of RPL settings throughout the network. The main objective of this strategy is to improve the effectiveness of important and critical healthcare applications.

We have developed and thoroughly tested our system using Contiki, which is an open-source IoT operating system. We have three instances in our MultiInstance RPL setup, each of which is intended to handle different kinds of network traffic and provide varying Quality of Service (QoS) measures. Different sets of Objective Function (OF) rules are used by each instance to decide which route is optimal for the data it processes. We have made use of OF0 (Objective Function 0) and MRHOF (Minimum Rank with Hysteresis Objective Function). We have rigorously tested our solution. Our focus has been on metrics like delay, average energy consumption and Packet Delivery Ratio (PDR). Compared to standard RPL, our approach improved packet delivery rates and significantly reduced delays for high priority data packets. This research shows how to better address the complex data traffic needs of real-time healthcare IoT networks.

Keywords: Internet of Things, RPL, Multiple Instances, Heterogeneous Traffic, LLNs, RDC and MAC Protocols

1 Preface

Over the past few years, the rapid advancements in IoT have sparked significant interest across various research domains, particularly IoT communication. Notably, protocols such as Bluetooth, ZigBee, and Wi-Fi, which boast low energy capabilities, have emerged as critical players. However, integrating LLNs utilizing 6LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks) presents unique challenges, including limitations on energy consumption, storage capabilities, and computational resources for embedded sensors. These connections often exhibit unreliability, characterized by significant packet loss and slow transmission rates [1][2].

The progress and expansion in the IoT domain face numerous obstacles, with routing standing out as one of the most difficult challenges. IoT encounters routing complexities influenced by energy consumption and interference when operating within a wireless environment.

In the healthcare sector, IoT technologies are instrumental in continuously monitoring and assessing patient data. Given this data's critical and time-sensitive nature, the need for dependable communication systems becomes paramount. These systems are crucial in ensuring continuous monitoring and prompt patient care provision. Therefore, healthcare networks require highly dependable routing protocols, given their constrained memory and energy resources [3][4].

Routing in LLNs often relies on RPL, a protocol specifically designed for such networks and standardized by the IETF in RFC 6550. The challenges associated with LLNs, including memory, energy, computational constraints, and unreliable connectivity paths, are effectively addressed by RPL. This protocol is capable of handling both Point-to-Multipoint (P2MP) and Multipoint-to-Point (MP2P) communication traffic, and it can scale to networks comprising thousands of nodes [5][6]. Unlike many Wireless Sensor Network (WSN) protocols like LEACH, CTP, and PEGASIS, which struggle with accommodating multiple applications, RPL excels in this aspect. Therefore, RPL emerges as the optimal choice for the project, instilling confidence in its suitability and effectiveness.

2 About the Routing Protocol - RPL

This routing protocol is an active distance vector-based routing protocol for networks that use 6LoWPAN technology. It breaks down the network topology into several easily comprehensible tree structures referred to as DODAG, which stands for Destination Oriented Directed Acyclic Graph. Every DODAG represents an instance of RPL; All the DODAGs are equipped with a specific optimization criterion aimed at refining the network's topology based on metrics such as shortest routes, network link reliability, and number of hops [7][8]. The focal point of each DODAG is the root or sink node.

In an RPL network, the root node, often called the border router (LBR), is the bridge to external networks. It serves as the main link to external networks. Positioned at the edge of the RPL network, the LBR facilitates communication between two distinct networks. The LLN typically connects to the external domain, comprising the IPv6 network or the Internet, through the DODAG root. A multi-hop mechanism engages other nodes as parent nodes when direct communication with the LBR is unattainable.

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The effectiveness of information transmission in the IoT network depends on the crucial operation of parent selection, which RPL manages.

Control messages are crucial packets essential in managing network stability by establishing and updating routing information. The trickle timer algorithm, coupled with these messages, ensures stability in the network.

RPL control messages encompass several categories, including:

DODAG Information Solicitation (DIS): New nodes do this, which initiates connection and participation within the network.

DODAG Destination Advertisement Object (DAO): These packets are optional and assist in establishing downward routes [8].

DODAG Information Object (DIO): This facilitates establishing, maintaining, and discovering DODAGs.

DAO-Acknowledgment control messages.

The RPL network orchestrates node arrangement to enable routing paths from all nodes down to the root.

Routing within RPL manifests in two primary modes:

- Upward Routing: This mode involves the transmission of traffic through nodes, where packets are forwarded directly to their preferred parent nodes, eventually reaching the network's root.
- Downward Routing: This process can be carried out in two ways: by maintaining a routing table at each node (also known as a solid mode) or by handling it centrally at the root node (also known as a non-storing mode). Downward traffic is predominantly employed for overseeing network control, retrieving data, and enabling end-to-end communication objectives [9].

Routing strategies within RPL are tailored using objective functions, which determine how nodes select preferred parents and calculate their ranks. Standard objective functions such as MRHOF and OF0 are utilized for routing in RPL. MRHOF typically relies on the expected transmission count (ETX) measure, and this concept deals with the reliability of packet transmissions required to reach the destination without errors. On the other hand, OF0 adjusts rank increments based on Hop Count [10][11].

Default OFs in RPL are tailored to consider a single metric. This may lead to compromised routing performance, particularly in IoT setups with diverse quality of service requirements within a unified network [58]. Furthermore, these OFs, which were initially designed for networks with minimal data flow, encounter significant challenges in larger network configurations. Despite RPL's flexibility in accommodating multiple metrics for parent selection, predetermined criteria for metric combinations remain unspecified [12].

2.1 Establishment of DODAG in RPL: The Foundation of Network Structure:

The creation of DODAGs in RPL initiates when the LBR broadcasts DIO control packets to nearby nodes. These packets contain vital details, including node ranks and distances, including those of the root node, which are essential for establishing the DODAG structure [12].

After receiving a DIO packet, neighboring nodes evaluate their proximity to the root. The next hop is set to be the root, and the packet is routed to nearby nodes. The individual receiving node uses the packet's information and identifies its next hop towards the root. This sequence continues until all nodes are incorporated into the DODAG [13].

RPL's operating approach focuses on creating channels directly connecting to the root. A node has to transmit a Destination Advertisement Object (DAO) to its immediate superior node to allow downstream traffic while retaining access to parent nodes. The Destination Advertisement Object (DAO) details node prefixes in its subDODAG. Upon reaching the root, these prefixes undergo aggregation. Additionally, RPL nodes can dispatch DODAG Information Solicitation (DIS) communications to neighboring nodes, soliciting DIO communications. Figure 1 illustrates the process of DODAG creation in RPL.

2.2 Instances in RPL

One or more DODAGs, which function as a logical arrangement of these structures, are included in an RPL instance. Every DODAG in an instance has its own RPLInstance ID. To verify DODAG coherence, unique DODAG IDs are assigned to each DODAG in a model. Within RPL, these identifiers are shared via the IPv6 protocol [14].

A single instance of a DAG can have more than one RPL node participating in it. Each RPL entity is associated with a unique Objective Function (OF), enabling the creation and classification of different DODAGs within the same topology.

2.3 RPL Multi-Instance

In real-world scenarios, different applications might generate various types of network traffic, each having particular Quality of Service (QoS) requirements. To address this,

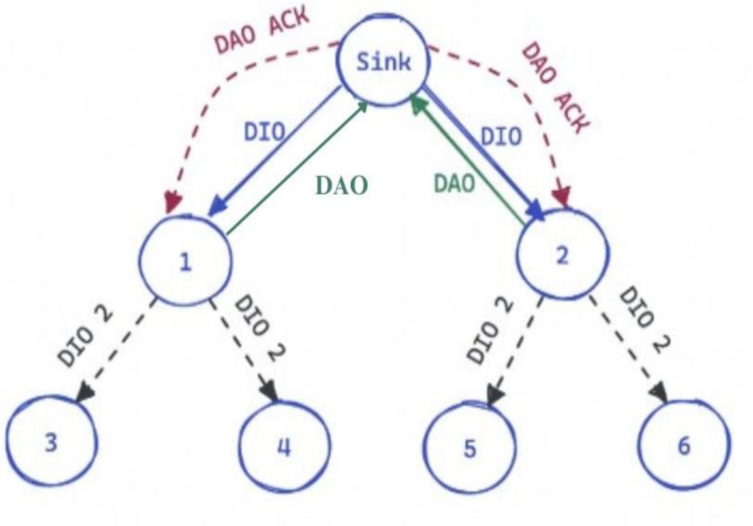


Fig. 1 Formation of DODAG in RPL

RPL enables the generation of numerous instances within a single network, each featuring a unique objective function. This flexibility enables a single physical network to support diverse routing metrics and topology. Within a multi-instance RPL network, every node oversees multiple routing tables tailored to different objective functions. To route data effectively in a multi-instance RPL network, a leaf node must do two things when it receives a packet. It should decide which routing instance best fits that type of data and use the relevant routing table within that instance to figure out where to send the packet next [12,15]. Figure 2 demonstrates this concept within the architecture of a multi-hop LLN, where the LBR connects the 6LoWPAN network to the broader internet. It should be noted that RPL does not support multiple instances by default. Modifications to the default protocol and routing methods are made to accommodate various use cases.

3 Related Works

In a 2019 publication ”Enhancing IoT-based Systems through Multiple RPL Instances,” Al-Abdi, et al. [14] delve into the advantages of supporting numerous RPL instances. Utilizing simulations via the Cooja Simulator, they establish a baseline of enhanced performance, focusing on Packet Delivery Ratio (PDR) across varying Received Signal Strength Indicator (RX) values and traffic types using multiple RPL instances. Their study underscores the need for more than a single RPL instance to handle critical data traffic effectively.

In 2017, Nassar et al. [15], in their paper ”Towards Efficient Quality of Service with Multi-instance RPL for Smart Grids,” introduced OFQS, an objective function designed to adapt to different traffic classes and deliver Quality of Service (QoS) distinctions customized to the diverse needs of smart grid applications. OFQS employs

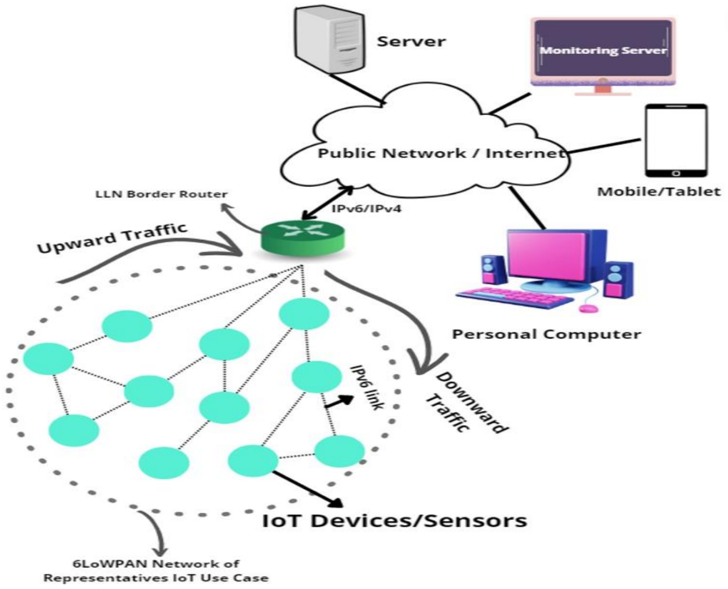


Fig. 2 Multi-hop Low-Power and Lossy Network (LLN) architecture)

a multi-criteria metric that considers factors such as available energy in battery nodes, delay, and network quality, resulting in an extended network lifetime, higher packet delivery ratio, and reduced latency.

Mardini et al. [17], in 2021, established multiple RPL instances grouped by traffic class. Their approach assigned critical data to the first instance and low-priority and periodic data to the second, resulting in superior average PDR across all RX values compared to single-instance RPL. Notably, critical data traffic experienced marked improvement and significantly reduced average latency.

In 2020, Bhandari et al. [18] proposed various OFs to ensure network-level quality of service differentiation. Their approach involved dividing the network into several RPL instances, each accommodating different traffic types with distinct OFs. Additionally, they introduced a novel framework, parent node selection, employing multi-attribute decision-making criteria, significantly reducing packet loss, delays, and reliability issues while ensuring minimum overhead and network stability, unlike default RPL.

Bouzebiba and Lehsani [19], in their 2020 paper ”FreeBW-RPL: A Novel Objective Function for Multimedia IoT,” introduced FreeBW. This function selects routing paths based on the required bandwidth for quality of service routing. FreeBW-RPL improves multimedia applications by dynamically selecting the most suitable forwarding candidate based on available free bandwidth information, hence decreasing congestion and improving performance measurements like end-to-end delay, Packet Delivery Ratio, throughput and energy consumption compared to conventional RPL.

Talking about 2019, Brandon Foubert [21] proposed a technique to enhance redundancy for border routers using a virtual DODAG. This approach enables multiple border routers to participate in a single DODAG, thereby synchronizing their parameters and allowing congested border routers to offload and distribute traffic to neighboring ones. This method improves the overall end-to-end and Media Access Control (MAC) Delivery Ratio by mitigating link-layer errors, surpassing the performance of RPL alone.

4 Proposed Approach

This research proposes a novel network architecture incorporating three distinct channels within the overall structure. They are known as Instance-1, Instance-2, and Instance-3 channels. Each provides a particular kind of information.

Consider a data transmission system that is a multi-lane highway. Instance-1 serves as the express lane, giving priority to urgent communications. This lane layout aims to reduce hold-ups and guarantee the quickest delivery of vital information. Conversely, instance 2 is the standard channel for critical information that is only sometimes time-sensitive. This lane ensures timely delivery while preserving network resources by finding a compromise between efficiency and speed. As the high-occupancy vehicle lane, instance-3 prioritizes efficiency for infrequent changes that use little bandwidth and least critical and non-time-sensitive data.

To evaluate the efficiency of this three-channel approach, we carried out a comparative analysis. Using Instance-1, Instance-2 and Instance 3, our system was compared against a standard RPL network that employs two separate channels. In the standard network, one channel prioritizes speed for all data traffic, regardless of its criticality. This prioritization is achieved through a metric known as Expected Transmission Count. The other channel, like Instance-3, focuses on efficient data transmission for routine updates using Hop Count as a metric. This comparison allows us to evaluate the benefits of our three-channel design in optimizing network performance for diverse data types.

4.1 Experimental Setup

Contiki OS lacks native support for multiple RPL instances; however, we have created a solution that allows this feature. We concentrated on making data flow smoothly upwards in the network. To give critical data that extra push, we combined NullRDCMAC with ContikiMAC. We also assigned specific roles (called objective functions) to different instances: MRHOF would take care of the super important and urgent data packet, while OF0 would handle regular traffic and routine updates. Figures 3 and 4 illustrate our experimental setups to compare single-entity and multi-entity scenarios. For the first scenario, we established a baseline using Contiki OS’s default protocol settings, including ContikiMAC and CSMA, representing a standard network configuration. We introduced a more sophisticated approach in the second scenario by employing multiple instances to prioritize critical traffic. To achieve this, we customized the NullRDC protocol, tailoring it to the specific needs of our experiment.

4.2 Simulation methods and Experiments

To test how well our proposed approach works, we did several simulations using the Cooja simulator within a Contiki 3.0 OS environment. Each simulation involved a

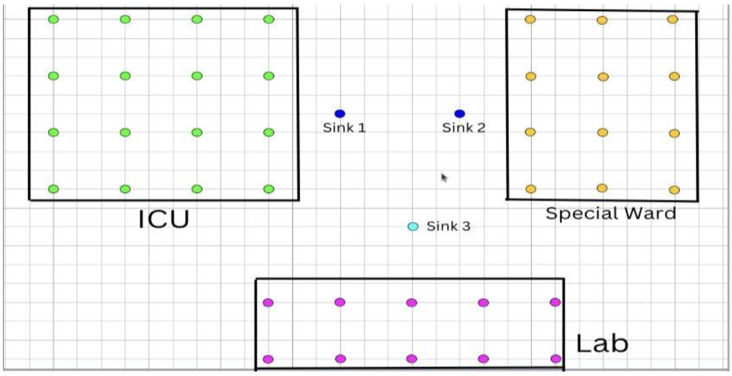


Fig. 3 Nodes dispersed across a 300 * 300 meter expanse

network topology consisting of 41 Zolertia motes strategically positioned across a 300m by 300m area (refer to Figure 3). Three designated sinks acted as data collection points.

We segregated the network into the following zones:

- ”ICU” (16 motes): Designated for critical data generation (Instance 1).
- ”Special Ward” (12 motes): Designated for important, but less time-sensitive data (Instance 2).
- ”Lab” (10 motes): Designated for routine updates (Instance 3).

Motes generated UDP data packets at frequencies determined by their assigned zone (Table 1). We configured radio transmission and interference ranges to be 50m and 100m, respectively. Reception success ratios varied from 20% to 100%, while the transmission success ratio remained fixed at 100%.

Table 1 Recommended transmission intervals and proposed packet payload sizes.

Motes Count	Objective Function	Size of Payload	Transmission Interval	Type of Traffic	RPL Instances
16	MHROF (ETX)	16 Bytes	15 Seconds	Critical	Instance 1
12	MHROF (ETX)	32 Bytes	30 Seconds	Non-Critical	Instance 2
10	OF0 (HC)	48 Bytes	180 Seconds	Periodic	Instance 3

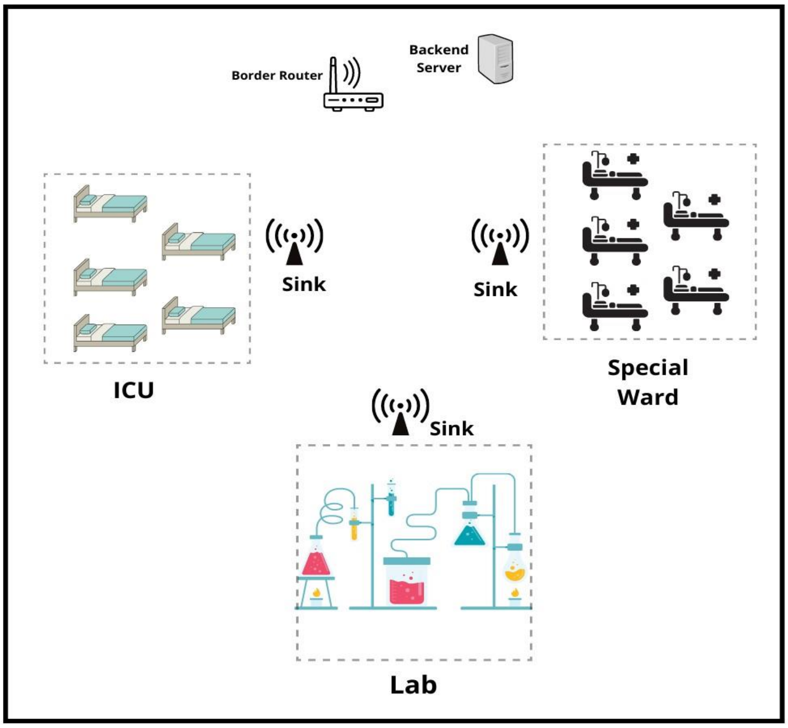


Fig. 4 Visualization depicting the arrangement of sensors in a hospital setting.

5 Experimentation Results and Interpretation

We tested how well our modified RPL network works under various conditions. We will look at a basic network setup (single instance) and our special version with multiple channels (multiple instances) to see which handles things better.

To measure and compare how well the network is doing, we will track the following metrics:

Packet Delivery Ratio (PDR): The proportion of messages successfully reaching their intended destination in comparison to the number of messages transmitted. Think of it like our mail delivery success rate.

Average End-to-End Latency: The time it takes for messages to traverse the entire network

Handling Different Data Types: We will specifically test how our multiple-instance RPL handles a mix of data (urgent vs. routine). It varies according to the size of the packet and packet send interval. This is known as heterogeneous data.

Formulas:

We'll use this equation to calculate PDR. It indicates the overall health of the network [9]: [Equation 1]

Table 2 Simulation environment for networks and their corresponding parameters

Simulation Parameter	**Values**
Type of Operating System	Contiki 3.0 / Ubuntu 21.04
MAC Layer	CSMA with Collision Avoidance
Radio-Duty Cycle	NullMAC and ContikiMAC
Physical Layer	IEEE 802.15.4 (Channel 26), CC2420 2.4 GHz
Mote Device Model	Z1 Zolertia
Network Layer	IPv6, ContikiRPL
Adaption Layer	6LoWPAN
Number of Sink Node	3
Number of Sender Nodes	38
Reception Ratio	Varying from 30%, 50%, 70%, 85%, and 100%
Transmission Ratio	Fixed at 100 %
Interference range for every Instance	100 m
Transmission Range for every Instance	50 m
Simulation duration	2700 Seconds
Deployment Coverage Area	300 X 300 m
Wireless Channel	Loss of Distance in the Unit Disk Graph Medium (UDGM)
Objective Function (OF)	MHROF – ETX, OF0 – Hop Count

Table 3 RPL instances set up with diverse RDC and MAC protocol configurations.

RDC Protocol	MAC Protocol	Type of Data Traffic	Objective Function	RPL Instances
ContikiMAC/NullMAC	CSMA	Critical	MHROF (ETX)	Instance 1
ContikiMAC	CSMA	Non-Critical	MHROF (ETX)	Instance 2
ContikiMAC	CSMA	Periodic	OF0 (HC)	Instance 3

Table 4 Proposed method for facilitating multiple RPL instances.

Reliability	Maximum allowed Delay	Type of Data Traffic	Instance Classification
90% to 100%	5 seconds	Critical	Instance 1
90% to 100%	5 seconds	Non-Critical	Instance 2
No strict reliability constraints	Periodic	1 to 5 minutes	Instance 3

$$PDR = \frac{TotalPacketsReceived}{TotalPacketsSent} \times 100 \qquad \text{(Eq.1)}$$

End-to-End Latency: This is the overall duration for a communication to move from its origin to its ultimate destination. We analyze the average latency to evaluate The network's overall performance with respect to speed and time taken to reach the destination.

Energy Consumption: This is how much energy a node uses when talking to other parts of the network, sending either regular messages or control messages. Since these nodes have limited power sources, keeping track of energy use is important[10].

5.1 PDR

Our results show that the MRHOF function's network instance delivers more messages successfully (higher Packet Delivery Ratio, or PDR) than the one using OF0. We tested this at a low packet reception ratio (30%) to make things challenging and facilitate real-world-like circumstances. To really see how well MRHOF and OF0 handle harsh network conditions, we tested them with different packet reception ratios. MRHOF held firm, delivering messages consistently – it is the reliable choice if the network is expected to have weak and unreliable connection. OF0 was less predictable, with its PDR sometimes dropping as the packet reception ratio changed. Figure 5 shows our findings. As we can observe from the graph, MRHOF consistently outperforms OF0 in terms of PDR across different conditions.

The comparison between MRHOF and OF0 regarding PDR is effectively depicted in Figure 5, highlighting MRHOF's advantages across diverse conditions.

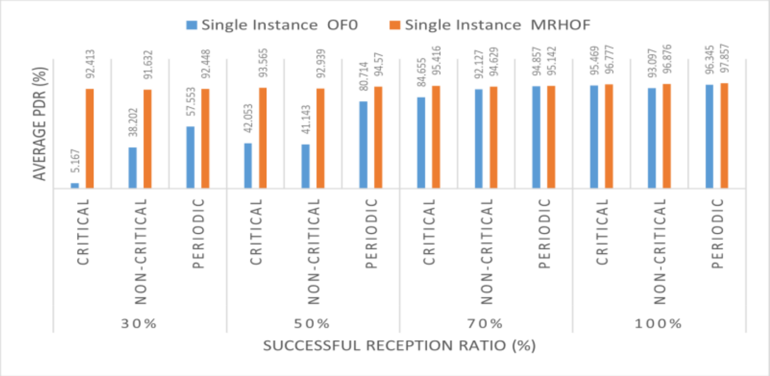


Fig. 5 Packet Delivery Ratio (PDR) for a single instance with varying Objective Functions such as OF0 and MRHOF

5.1.1 Scenario 1: Routing Protocol for Low-Power and Lossy Networks instances established with typical default Medium Access Control (MAC) and Radio Duty Cycle (RDC) Protocol.

We commence by employing RPL instances pre-configured with typical RDC and MAC protocols. MAC protocols, such as TDMA and CSMA, act as the network traffic controllers, governing the communication between devices. Precisely, in wireless networks, the CSMA/CA (Collision Avoidance) protocol consists of a set of regulations aimed at averting data collisions when multiple devices endeavor to access the network concurrently.

On the other hand, RDC is like a power-saving feature. It tells the devices when to sleep and when to be active to receive messages. The traditional RDC usually follows a simple on-and-off pattern to keep the devices from draining their batteries.

When using the default setup, the parameters controlling these protocols come with preset values. These parameters are the fine-tuning knobs that govern how the protocols work and how the devices in our network interact. The defaults are chosen based on the type of wireless network and how much data you expect to be flowing through it.

In short, using the standard MAC and RDC protocols with RPL is a good starting point for LLNs. However, for specific situations, we need custom MAC and RDC protocols to fine-tune the network and get the best performance for your application. Healthcare is one such case.

Our experiments showed that with a single instance of RPL, once the ReceptionRatio (RX) dropped below 70%, PDR suffered, especially for critical and non-critical traffic – it fell below 50% due to the weak connection. Our proposed Multiple Instance RPL maintained a PDR of over 90% for both critical and non-critical traffic, even in the presence of a weaker signal.

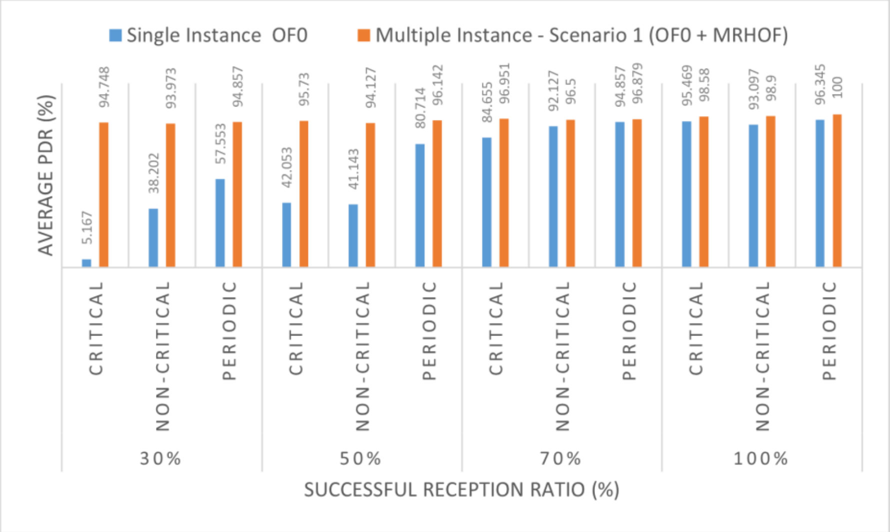


Fig. 6 Scenario 1 Packet Delivery Ratio for Single Instance and Proposed Multiple Instance

Using the Hop Count metric for periodic traffic with the Multiple Instance approach also maintained high PDRs even with low RX ratios. Figure 6 shows the average PDR across various data types (critical, non-critical, periodic) for both single and Multiple Instance RPL. Our setup shows that PDR in the Multiple Instance setup is higher for critical and periodic traffic.

Overall, our Multiple-instance method consistently provided a superior PDR for both critical and non-critical data transmission compared to the single-instance method, particularly under weak signal conditions. Also, the Hop Count metric within our Multiple Instance setup delivered better PDR for periodic traffic, even with a low RX ratio. This demonstrates that using Multiple Instances and choosing the proper objective functions can significantly boost LLN reliability and efficiency.

5.1.2 Scenario 2: RPL Instances configured with NullRDC and MAC Protocol

NullRDC and MAC protocols offer alternatives to the usual MAC and RDC protocols for RPL instances. The NULLRDC driver is a simple RDC driver in Contiki that does not implement any duty cycling or radio power management. It effectively disables any duty cycling, making the radio continuously available for communication. The MAC protocol, in turn, handles the organization of the wireless channel, ensuring devices do not collide when trying to communicate. Pairing NullRDC and MAC together creates a more robust and reliable interface for the transmission of data packets.

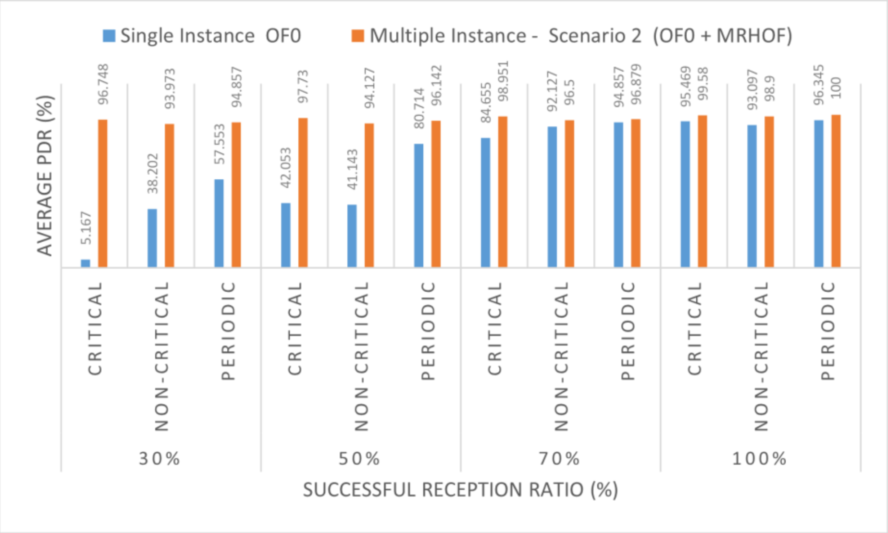


Fig. 7 Packet Delivery Ratio (PDR) for a Singular Instance and Proposed Multiple Instances utilizing NullMAC

Setting up RPL with NullRDC and MAC allows us to measure the network's performance. We can look at metrics like:

Packet Delivery Ratio (PDR): How many packets reach their destination compared to how many were sent.

Average End-to-End Latency: The overall duration for a packet to traverse the network.

Throughput: The overall amount of data the network can handle.

In scenario 2, Multiple Instances for Critical Traffic are set up with the NullRDC protocol, keeping the radio active for transmitting Critical Traffic. This may result in increased energy consumption. Figure 7 compares the PDR of a Single Instance and Proposed Multiple Instances with NullMAC. Notably, the Packet Delivery Ratio (PDR) indicates the proportion of received packets compared to those sent.

Our simulation findings indicate that in a single instance configuration when the reception ratio (RX) falls below 70%, there is a notable decrease in the overall Packet Delivery Ratio (PDR) due to the diminished connection quality. This decline impacts both Critical and Non-critical traffic, resulting in PDR values dropping below 50%. However, implementing our proposed Multiple Instance RPL utilizing NullRDC effectively maintains a higher Packet Delivery Ratio for both critical and non-critical traffic, even with lower RX values. This underscores the advantage of the Multiple Instance approach in terms of PDR compared to the basic Single Instance model. While maintaining radio activity for Critical Traffic via NullRDC enhances reliability, it naturally increases energy consumption.

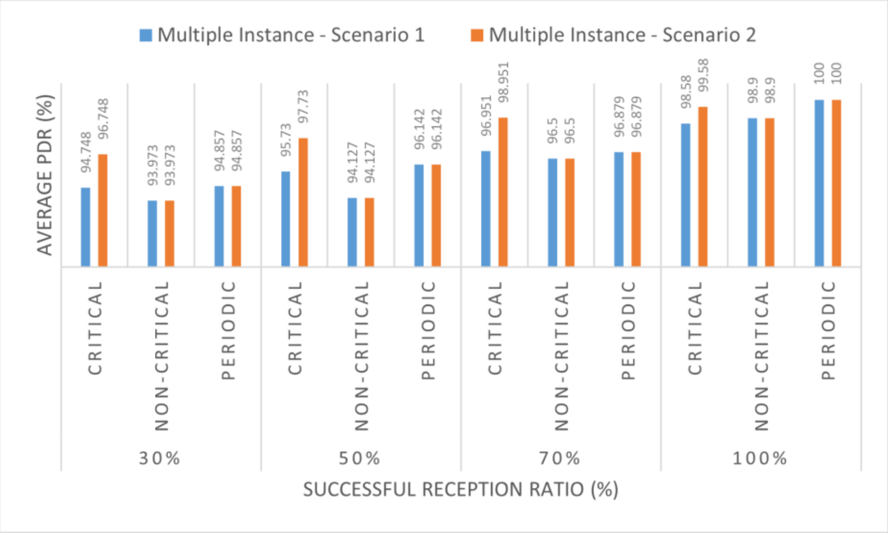


Fig. 8 Packet Delivery Ratio (PDR) for Proposed Multi-Instance – Scenarios 1 and 2

Our proposed Multiple Instance approach has broader applications beyond the scenarios tested here. Figure 8 showcases the PDR comparison between Scenarios 1 and 2, demonstrating that Multiple Instances with NullRDC consistently outperform a Single Instance setup. It delivers higher PDR across all traffic types, regardless of signal strength (RX).

These results emphasize the effectiveness of our Multiple-instance approach with NullRDC for routing Critical Traffic. It guarantees higher PDR and minimizes packet loss and delays. Although there is a trade-off in energy consumption, the gains in reliability are significant. Overall, the findings highlight the paramount importance of MAC and RDC protocol choices in maximizing routing efficiency, mainly when dealing with critical data.

5.2 Average Latency

We evaluated our proposed multiple instances method for handling different traffic types (critical, non-critical, and periodic) across various signal strengths (30% to 100% reception). It proved to be much better than the traditional single-instance RPL approach. We also found that MRHOF has significantly lower latency than OF0 when dealing with standard single-instance network traffic.

The multiple instances approach showcased an average latency of nearly 0.1% of that observed in single-instance RPL. This signifies a considerable reduction in the latency as compared to the current method. Table 5 outlines the average latency comparison between the proposed and existing systems.

This method improves the system's overall performance by lowering end-to-end delay significantly. Because of how well packets are routed over the network, latency has decreased. The MRHOF objective function takes into account both network reliability and hop count. This makes such results feasible.

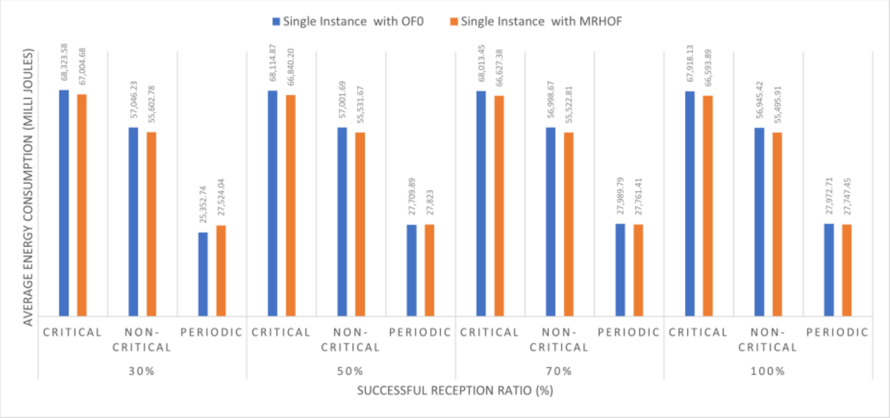
Large-scale IoT networks can benefit from the many instances of scalability of methods. This allows it to handle a variety of traffic types and scenarios. It enables routing techniques to be tailored for particular traffic kinds, thus maximizing the use of network resources. As a result, the multiple instances method shows promise for improving the performance of IoT networks by outperforming single-instance RPL in terms of average latency and packet delivery ratio for all traffic categories. Successful Reception Single Instance Proposed Multiple Type of Data Traffic

Ratio	OF0	MRHOF	Instances	
100%	33.6	30.4	0.0273	Overall Traffic
85%	37.1	32.7	0.0281	Overall Traffic
70%	39.8	34.5	0.0314	Overall Traffic
50%	41.5	37.8	0.0348	Overall Traffic
30%	43.1	40.1	0.0375	Overall Traffic

5.3 Average Energy Consumption

Figures 9, 10, and 11 depict how much more energy efficient the single instance approach is when using MRHOF than when using OF0. Additionally, in both Scenario 1 and 2, the multiple-instance setup consistently uses less energy on average than the single-instance approach – this holds regardless of signal reception strength.

The enhanced energy efficiency of the MRHOF-based single-instance approach stems from its consideration of communication link quality, a factor overlooked by OF0. Consequently, MRHOF can establish more robust communication paths with



Average power consumption for a single instance with varying objective functions such as OF0 and MRHOF.

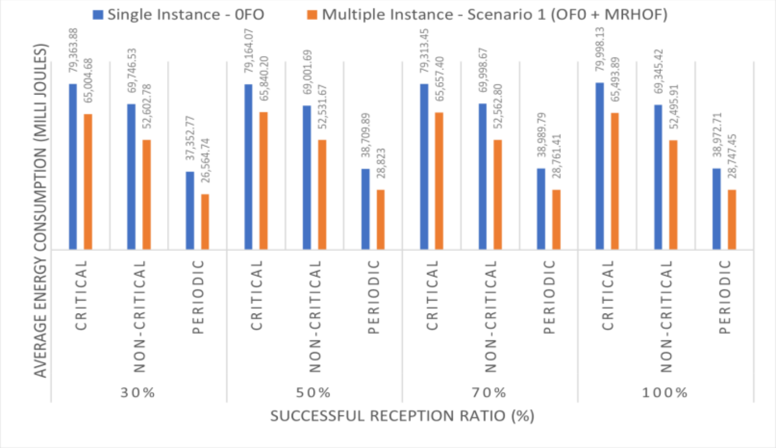


Fig. 9 Average energy usage for a single instance and proposed multiple instances – Scenario 1.

fewer retransmissions, particularly at lower reception ratios, substantially reducing energy consumption. This observation aligns with prior research highlighting MRHOF's efficacy in enhancing energy efficiency in low-power wireless networks. The multiple-instance approach boosts network energy efficiency by providing several routes for data to travel simultaneously. This spreads out the workload, so every path gets manageable. This makes the network more reliable and less likely to fail—which is extremely important for applications where downtime is not an option.

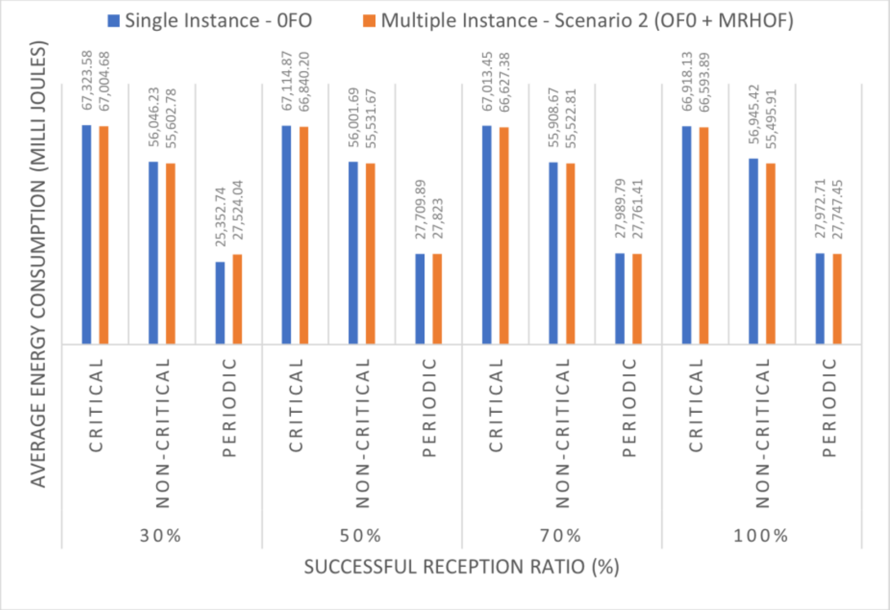


Fig. 10 Average energy consumption for a singular instance and the proposal of multiple instances – Scenario 2.

To sum up, Figures 9, 10, and 11 demonstrate that the proposed multiple-instance approach using MRHOF is significantly more energy-efficient than the traditional single-instance approach using OF0. This advantage is especially noticeable when signal quality is weaker.

6 Conclusion

Our research offers a new solution to the complex problem of managing diverse types of data in healthcare environments that use LLNs. We propose refining the existing RPL protocol to better handle different types of traffic.

We conducted a thorough analysis comparing two routing methods – MRHOF and OF0. MRHOF consistently outperformed, underscoring the importance of considering link quality when making routing decisions. Additionally, we tested NullRDC MAC against the traditional ContikiMAC for handling critical ICU data. NullRDC MAC proved faster and more reliable but at the cost of increased energy consumption.

Our methodical methodology blends multiple strategies to address the difficulties presented by LLN healthcare scenarios. Together with the Null-RDC MAC, we strategically use both MRHOF and OF0 to handle various traffic types, resulting in an effective healthcare system that caters to the unique needs of the networks.

This study introduces a novel strategy for efficiently managing the complexities of mixed traffic in healthcare LLNs. The results show significant performance improvements, particularly for critical data. This signifies a promising step forward and lays the groundwork for future research in the field.

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