RPL Objective Function for Multihop PLC Network

Mingyu Park, Gunmo Jeong, Omprakash Gnawali, and Jeongyeup Paek

***Abstract*—The increasing number of devices in the Internet of things (IoT) is beginning to exhaust the wireless channel. As an alternative, power line communication (PLC) appears promising and has the potential of providing easy deployment at low cost. On one hand, PLC resembles wireless low-power and lossy networks (LLN). Its performance is time-varying and sensitive to noise, interference, and asymmetry owing to co-existing electronic appliances. However, when running the standard IPv6 routing protocol for LLN (RPL) on PLC, the network suffers significant reliability loss because RPL does not reflect the unique characteristics of PLC. To address this problem, we propose *PLC-OF*, an objective function (OF) for RPL over PLC. *PLC-OF* exploits PLC's physical layer (PHY) *diversity* as a routing metric distinct from other approaches in wireless. *PLC-OF* finds the most suitable path to prepare for sudden interference or congestion in power lines. Evaluation results from real testbed experiments show that *PLC-OF* better tolerates noisy medium compared to existing objective functions. Particularly, *PLC-OF* has better reliability (≈10%) and robustness with less channel usage (≈30%) than that of ETX-based MRHOF in highly congested environments.**

***Index Terms*—IPv6, Internet of Things (IoT), Low-power and Lossy Network (LLN), PLC Network, Routing Protocol for LLN (RPL).**

I. INTRODUCTION

INTERNET of things (IoT) has become ubiquitous owing to the recent advances in embedded and communication technologies. Most IoT devices use wireless communication such as Wi-Fi, Bluetooth, and Zigbee/IEEE 802.15.4. However, as the number of IoT devices increases rapidly over time, the ISM band has become crowded and insufficient to support the increasing demand. Furthermore, IoT applications such as smart factory, smart market, smart hospital, in-vessel communication, and smart grid AMI [1]–[3] may occur in environments where surrounding metal walls, shelves, and machinery obstruct or hinder wireless communication; hence, power line communication (PLC) attracts attention as a potential alternative of wireless.

An outstanding advantage of PLC is that it uses existing power lines as its communication medium. This does not only save significant cabling costs; it is also free from wireless interference. Furthermore, wireless cannot communicate through walls or metal obstacles whereas power lines are installed in buildings through walls. Thus, PLC can potentially communicate to any device connected to a power outlet. Because of these benefits, PLC is widely used for IoT applications such as smart city and streetlight systems [4]. Fig. 1 illustrates the example of an IoT-based smart grid AMI system over PLC that is currently being deployed by a major electricity service provider [1].

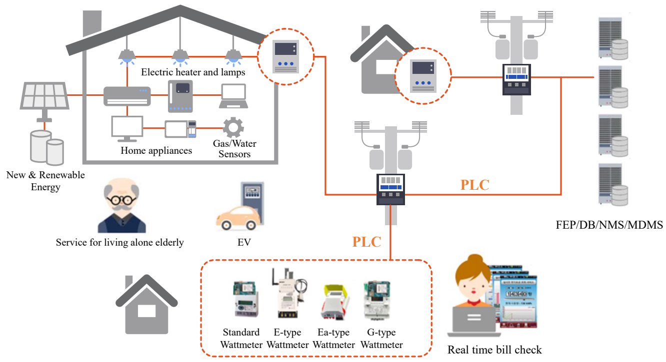

Fig. 1. IoT/AMI solution over PLC.[1]

Despite the benefits, PLC possesses some characteristics that need to be considered before it is utilized in real-world IoT applications. Although it seems power is connected seamlessly throughout the building, PLC is often blocked or disrupted by circuit breakers or transformers. Thus, repeaters, relays, or gateways are required to forward messages over *multi-hop*. Furthermore, PLC is exposed to additional noise and interference in the power lines owing to factors such as fluctuating electricity usage by co-existing power-consuming electronic appliances (e.g., refrigerator or air conditioners), which are *time-varying and asymmetric* [5], [6]. Therefore, PLC somewhat resembles wireless multihop low-power and lossy network (LLN) environment, but has additional challenges due to non-communication power usage.

Because the scale of PLC network expands with LLN-like characteristics, a multihop routing protocol is required. For this purpose, and to become a part of IoT, the Internet standard *IPv6 routing protocol for LLN (RPL)* [7], [8] is used to provide end-to-end IPv6 connectivity to resource-constrained embedded devices. However, RPL on PLC faces significant reliability challenges because RPL does not reflect the unique characteristics of PLC.

In RPL, devices select and optimize routes based on a predefined decision rule called *objective function (OF)*. RPL

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[1] Power Line Communication Solution for IoT by KEPCO KDN, https://www.kdn.com/menu.kdn?mid=a20106040000

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standard only defines a default OF zero (OF0) [9] for compatibility, and is often replaced with a better OF [10] such as *minimum rank with hysteresis objective function* (MRHOF) [11]. Several studies [12]–[16] have proposed novel OFs to improve RPL's performance; however, these works are designed based on 'IEEE 802.15.4 wireless' links. Therefore, a new PLC-applicable OF is needed to reflect the unique characteristics of PLC distinct from IEEE 802.15.4 or other wireless [5], [6].

To this end, we propose *PLC-OF*, an OF for RPL that is suitable for PLC environments. *PLC-OF* exploits PLC's physical layer (PHY) *diversity* as a routing metric distinct from other approaches in wireless, and finds a suitable path to prepare for sudden increase in noise and congestion in power lines. PLC uses the *diversity* feature for reliable data delivery which varies sensitively to link quality and directly affects data rates (up to 15 times) [17]. *PLC-OF* considers this *diversity* to achieve higher data rates and prevent bursts, congestion, and load imbalance. We implement *PLC-OF* on 12 real embedded PLC devices designed by CNU Global corporation [18], and evaluate its performance through an extensive set of experiments. The results show that *PLC-OF* has improved reliability (≈10%) and robustness with less channel usage (≈30%) than *expected transmission count* (ETX) [19] based MRHOF in a highly congested environment.

The contributions of this paper are as follows.

- We experimentally show the time-varying and asymmetric characteristics of PLC links using real devices.
- We propose *PLC-OF* for RPL over PLC which uses PLC's PHY layer *diversity* as a new link and path metric with a load balancing scheme for selecting reliable routes.
- We implement *PLC-OF* in real embedded devices, and evaluate its performance through experiments on a 12 node PLC testbed.

The remainder of this paper is organized as follows. Section II discusses previous studies and the motivation of this study. Section III presents the design of *PLC-OF*, and Section IV presents the evaluation results. Finally, Section V presents the conclusion of this paper.

II. Related Work and Motivation

This section first provides background and related work on PLC and RPL. We then discuss the characteristics of PLC through preliminary experiments which motivates our work.

A. Related Work

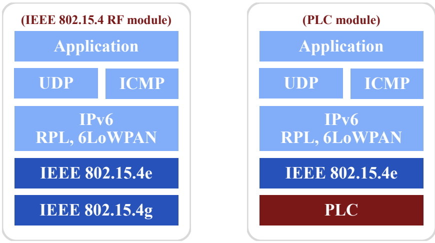
PLC network has several commonalities with LLN as mentioned in Section I. Accordingly, many real-world 'IoT-PLC' [17], [20] network stack architectures are designed to be similar to IEEE 802.15.4 based LLN except for the PHY layer as shown in Fig. 2. For example, Chauvenet *et al.* proposed a communication stack over PLC using IEEE 802.15.4 link layer for multi physical layer IPv6 networking [21], [22]. This is similar to the approach taken by Cisco Systems Inc. in their smartgrid AMI solutions [23] where IPv6 mesh network was designed over RPL, 6LoWPAN, and IEEE 802.15.4 on dual wireless and PLC physical layers. However, these studies reuse existing ETX based routing [19] without proposing a suitable metric for PLC.

The noise properties of PLC are highly time-varying because it is influenced by on-off usage of electronic devices [5], [6]. To address the time-varying noise in PLC, the PLC standard [17] specifies a PHY-layer technique called *diversity*. When a PLC transmitter transmits a data frame, it repeats the payload portion of the frame (excluding the PHY header) as many times as the value of diversity, similar in concept to repetition codes. If the PLC transmitter fails to receive an ACK for a few transmissions, it increases the value of diversity to improve link reliability. Conversely, if the PLC transmitter successfully receives ACKs for several consecutive transmissions, it decreases diversity to reduce channel occupancy and improve effective throughput. According to the standard [17], diversity ranges between 1–15; thus, effective throughput can vary up to 15 times (not accounting for the header part). Therefore, finding a clear channel is necessary to prepare for losses caused by noise and achieve higher data rate.

RPL [7] is an IETF standard IPv6 routing protocol for lossy IoT environments consisting of resource-constrained embedded devices. It is a distance vector routing protocol that constructs a quasi-forest routing topology at a border router called root to support bi-directional Internet connectivity.

A RPL node finds the best route among its neighbors based on a predefined path selection rule called OF [10]. The performance of RPL varies significantly based on the OF used; hence, OF plays a crucial role in RPL. RPL standard specifies a default OF (OF0) [9] which must be implemented in every RPL node for minimal compatibility. It is a simple hop count-based scheme, resulting in choosing the shortest path to root without considering link qualities. A follow-up standard defines MRHOF [11] which by default uses ETX [19], [24] as a routing metric, and is used in many real-world IoT application and deployments. However, the RPL standard neither mandates any particular OF nor routing metric to be used, and leaves this open to implementations. Thus, it offers flexibility in meeting different optimization criteria required by a wide range of deployments, applications, and network design.

Several prior studies have developed OFs that suit their application objectives and environments for better performance [8]. Karkazis *et al.* [25] proposed simple and lexical combination of two routing metrics among hop count, ETX, remaining energy, and RSSI, and compared their trade-offs. QU-RPL [12] uses queue size of each node in the network as a routing metric to achieve both reliability and load balancing. OF-FL [26] is a QoS-aware fuzzy logic OF that combines a set of metrics to provide a configurable routing decision based on fuzzy parameters to support various application requirements. PC-RPL [15] designs distributed transmission power control to avoid load imbalance and congestion for improved reliability. In the context of PLC, there are some studies that implemented RPL over PLC network (or hybrid with wireless network) [27]–[29]. However, those studies



(a) IEEE 802.15.4 (b) PLC

Fig. 2. IoT stack architectures.

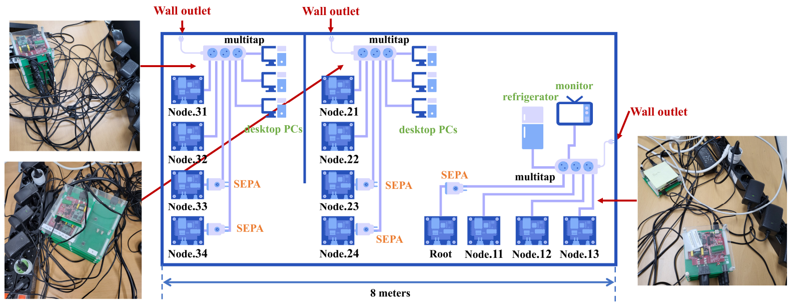
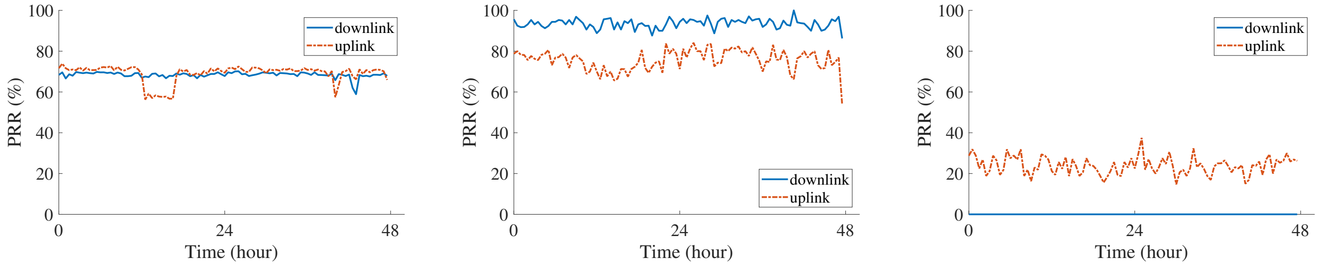


Fig. 3. 12-node multihop PLC testbed in a university lab.



(a) total (b) between node 11 (c) between node 12

Fig. 4. Link reliability from node 21.

have only proposed interface selection schemes, or evaluated performance of existing OFs (OF0 and ETXOF). To the best of our knowledge, there has been no study that uses diversity as a routing metric nor design of an OF appropriate for PLC networks.

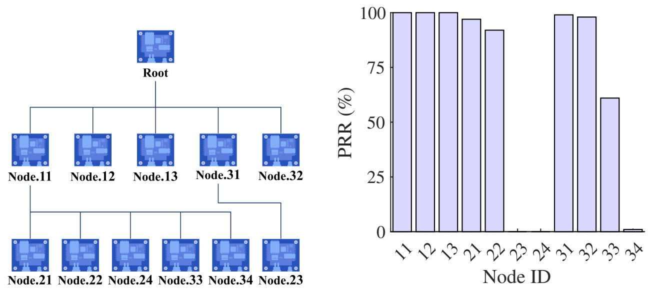
B. Motivation - Preliminary study

We conducted real experiments on a 12-node multihop PLC testbed (as illustrated in Fig. 3) to investigate the link characteristics and performance of RPL on PLC. We focus on our findings here, and describe the details of the testbed and evaluation setup later in Section IV-A.

Link reliability over time: First, we measured single-hop link quality for every pair of PLC devices for two days. In the experiment, a node selects a neighbor node and exchanges a frame per second for 10 seconds, and repeats this every couple minutes.

Link reliability results are plotted in Fig. 4. Fig. 4a is the average PRR of all links with non-zero PRR in either direction, excluding the links that never reached (0%) each other in both directions. It indicates that the aggregate link quality was relatively stable for most of the time but had a few abrupt changes that spanned a few hours. This was when we turned on a nearby server. Furthermore, PRRs of a link in opposite directions (denoted as uplink and downlink) may be different (by approximately 30%), and vary over time (by approximately 20%) as shown in Figs. 4b and 4c. Particularly, some links allow communication only in one direction (Fig. 4c). The observations demonstrate that PLC links possess asymmetry and time-varying characteristics.

RPL's performance: A default OF0-based RPL node chooses a parent from which it had received a DIO message (i.e.



(a) Routing topology (b) Packet reception ratio

Fig. 5. Performance of OF0 over PLC network.

routing beacon) as long as there is no shorter alternative path to the root. However, receiving a message "from" a node does not guarantee that it can send a message "to" that node owing to asymmetry. Thus, even if a node selects a parent upon reception of a beacon from that parent (downlink), the node may not be able to reach the root through that parent (uplink). To demonstrate this, we implemented RPL with OF0 and ran a multihop data collection experiment on the testbed consisting of one root and 11 sensor nodes, each sending a unique packet per second toward the root.

Fig. 5 plots the result of this experiment. Nodes 23, 24, and 34 attained 0% reliability; they were unable to deliver any packet on their link toward their respective parents. This is because the child node can hear their parents' beacon while the parent cannot receive the packets sent by the child; thus, OF0 does not reflect link reliability nor asymmetry in parent selection. Therefore, to apply RPL in real-world PLC applications and deployments, a new OF must be designed for multihop PLC environment.

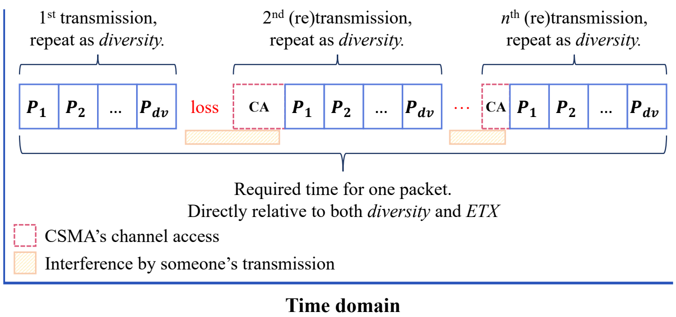


Fig. 6. Time required to transmit a packet successfully.

III. Design

In a multihop PLC network, finding a path with lower diversity is directly related to achieving reliability and higher data rate. So far in wireless, the ETX [24] metric has been used widely for similar purposes which estimates how many transmissions would be needed to deliver a message. In this section, we combine diversity with ETX as a route metric, and adopt a load balancing policy to design *PLC-OF*.

A. Link and path metric for PLC

Diversity and ETX work in a similar manner in the sense that they attempt to estimate the number of repetitions required to successfully deliver a message. However, diversity is a PHY-layer parameter while ETX estimates the number of link-layer transmissions. ETX is only an anticipated estimation and not the actual number of link transmissions. For example, if ETX is two, the message delivery may be completed early if successfully ACK'ed within the first transmission attempt; however, it could fail after the second transmission. Unlike ETX, a PLC transmission always repeats the message (payload) as much as the diversity value without early termination regardless of whether an earlier repetition was successfully received. Furthermore, a diversity-repeated frame is transmitted at one channel access. Conversely, ETX must retry accessing the channel using CCA/CSMA for every retransmission. Therefore, retransmission in ETX and repetition in diversity affect transmission time differently as illustrated in Fig. 6, and ETX usually has a more significant impact on the required time for successful message delivery than diversity. This is expressed as follows;

$$T_{\text{total}} = N_{tx} \times (T_{ca} + \text{diversity} \times T_{tx}), \quad (1)$$

where T_{total} represents the total required time to deliver a frame, T_{ca} is time to access channel using CCA, T_{tx} is the transmission time of a single frame, and N_{tx} refers to the actual number of (re)transmissions made for successful delivery.

Inspired by such characteristics, *PLC-OF* combines both diversity and ETX into a link and path metric to consider end-to-end reliability and throughput. Basically, *PLC-OF* multiplies diversity and ETX for the link metric. However, direct multiplication must be refrained owing to the following reasons. First, the unit of ETX is more influential in time usage for a successful transmission due to repeated channel access time (i.e. CCA and backoff). Second, the range of diversity (from 1 to 15) [17] is relatively larger than ETX (from 1 to 4 in default firmware parameter) and varies significantly. A wide and frequent variation of path metric leads to frequent route changes, which causes route inconsistency. Therefore, *PLC-OF* calibrates diversity as

$$DV_c = \lfloor (DV_m/\gamma) + 1 \rfloor, \quad (2)$$

where DV_c is the calibrated diversity, DV_m is the average measured diversity, and γ is the scaling factor which scales the diversity range to match that of ETX (from 1 to 4 in default firmware parameter). Through the calibration, the range of diversity is converted from $[1, 15]$ to $[1, 4]$ using γ of 5. Subsequently, *PLC-OF* multiplies ETX with the calibrated diversity for the per-hop link cost, and accumulates the link cost along the path for the path cost. Notably, both ETX and average measured diversity are calculated using exponentially weighted moving average (EWMA) to smooth the gradient.

$$Cost_{\text{link}} = DV_c \cdot ETX \quad (3)$$

$$Cost_{\text{path}} = \sum_{\text{link} \in \text{path}} Cost_{\text{link}} \quad (4)$$

B. Load balancing

Choosing the best link among several candidates with similar path cost is a local decision problem. However, from the multihop network's perspective, it may not always be the best choice for end-to-end performance. Suppose a device $Node_{\text{best}}$ is the best parent for all children nodes. Every child node will be attached to $Node_{\text{best}}$ after some route explorations, leading to a bottlenecked network. Then, network performance is degraded owing to congestion and contention although all nodes have selected their best quality parent. Consequently, transmission failures lead to an increase in ETX and diversity; thus, the children nodes misunderstand that the link to $Node_{\text{best}}$ became bad and look for an alternative. The nodes may stampede to the second-best node, and the vicious cycle is repeated. To address this problem, *PLC-OF* spreads the incoming traffic by applying a load balancing technique.

The proposed method modifies an idea from [30] which defines a stochastic routing domain selection algorithm that achieves a balanced tree topology. At every path calculation (for potential parent re-selection), a RPL node compares the size of each candidate subtree network and moves to the other network if the size of the network is smaller than the current network. However, to avoid the herding effect (that is, moving back and forth repeatedly), it switches network with the following probability.

$$Prob_{\text{switch}} = \frac{\alpha \times (Size_{\text{current subtree}} - Size_{\text{another subtree}})}{Size_{\text{current subtree}}}, \quad (5)$$

where α is a weighting factor to control the stickiness of devices attached to the current network. α can be used to control the tradeoff between responsiveness and stability in topology construction, and we use 1/2 to balance the two.

PLC-OF exploits this technique into path selection algorithm. In every route calculation, *PLC-OF* finds the best path and compares it with the current network. If the difference of

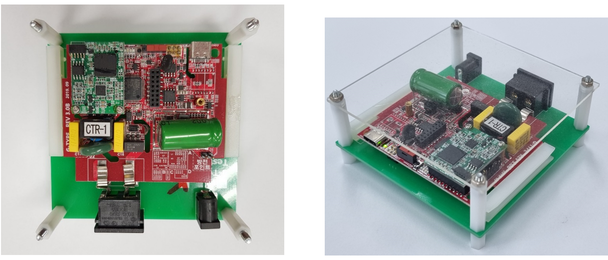


Fig. 7. PLC device developed by CNU GLOBAL Corp. [18].

path cost is greater than an average link cost (a hop), *PLC-OF* chooses the better path regardless of load balancing. However, if the difference is marginal and the size of other parents' subtree is smaller than its current parent, it flips a coin with probability $Prob_{switch}$ to decide whether or not to move.

IV. Evaluation

We evaluate *PLC-OF* by comparing it with two representative OFs, OF0 [9] and MRHOF [11], through testbed experiments. We focus on experiments since simulators do not reflect the unique power-usage characteristics of real PLC networks.

A. Experiment Setup

The experiments were conducted on a multihop PLC testbed consisting of 12 nodes (1 root, 11 sensor nodes) as illustrated in Fig. 3. PLC devices are connected to power outlets on the walls through multiple-taps. We used a device called 'SEPA', an electromagnetic wave filter [31] that attenuates PLC's signal strength to create a multihop topology in the lab. Five SEPAs are connected to the power lines going out from nodes 23, 24, 33, 34, and the root. Furthermore, electronics such as computers/servers, switches/routers, refrigerator, television, and two air conditioners are connected to the power outlets in the lab as they would regardless of the experiments.

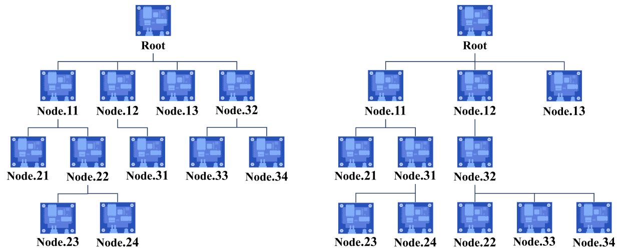
Each node is an embedded PLC device developed by CNU GLOBAL[2](Fig. 7) [18], and consists of a STM32L496 SoC and a CR100N PLC chip. PHY layer uses DQPSK modulation with a maximum transmission speed of 24 Mbps. It supports up to 360 bytes for payload (MAC data frame), and the length of the frame doubles once it passes through the convolutional turbo encoder. After encoding, PHY layer repeats the encoded data as many times as the value of *diversity* parameter. Therefore, it can only achieve ∼800 Kbps when the diversity value is 15 (roughly, not accounting for the PHY header part). Link layer uses CSMA that conforms to the standard IEEE 802.15.4 MAC. Both PHY and link layers are embedded in the device firmware. On top of this, we implement the complete IoT-PLC stack (Fig. 2) in Free-RTOS including IPv6, RPL, 6LoWPAN [32], IPv6 neighbor discovery, and the three OFs including *PLC-OF*.

The link and PHY layer parameters are listed in Table I. *Diversity success/fail count* represent the number of consecutive transmission success/failures required to trigger a diversity adaptation event. *Diversity up/down step* configure the increase/decrease diversity value when an adaptation event is triggered. For example, a PLC device reduces diversity value by 1 when it consecutively succeeds transmission three times. MinBE, maxBE, and max retx count are the regular CSMA parameters used to gain the channel and retransmit frames if necessary. According to the standard, PLC device always transmits full size (360 bytes) frames regardless of actual data length.

[2]http://www.cnuglobal.com

TABLE I
PLC's PHY/link parameters within the firmware.

Modulation	DQPSK
diversity range	1 – 15
diversity fail count	1
diversity down step	1
diversity success count	3
diversity up step	2
minBE	5
maxBE	10
max retx count	3
payload size	360 bytes



(a) when using MRHOF (b) when using *PLC-OF*

Fig. 8. Routing topology constructed by RPL with each OF.

The application used for evaluation transmits messages using UDP over IPv6 compressed by 6LoWPAN [32] after constructing the routing tree topology using RPL. Each sensor node generates unique data messages periodically and transmits them toward the root. The experiments were conducted with varying data rates from 2.5 pkts/s to 7.5 pkts/s[3], per node, with 0.5 increments. We measured (1) the number of received unique packets at the root for each node, (2) the number of (re)transmissions at each sender, and (3) the *diversity* value for every transmission during the experiments. From those measurements, we compared the three OFs in terms of packet reception ratio (PRR), relative channel usage, robustness to network failure, and control overhead.

- PRR is the ratio of unique messages received by the root from each node against the total number of messages.
- Channel usage is compared relatively by multiplying total transmission count with average diversity at each node.
- Robustness to node failure is observed by examining per-minute PRR while deliberately destroying a node to off state.
- Control overhead is expressed as a fraction of total packets in the network devoted to controlling messages.

[3]Data generation rate of 7.5 pkts/s (excluding multihop forwarding traffic) was the highest that the current version of the PLC devices were able to handle when 11 nodes were transmitting near-simultaneously over multihop (that is,. 150∼200 pkts/s for the network).

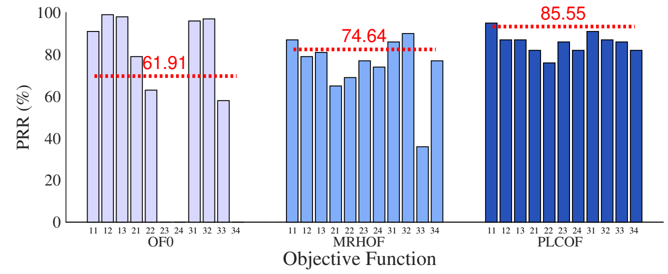


Fig. 9. PRR of each node for the three OFs with 7.5 packets per second per node data generation rate.

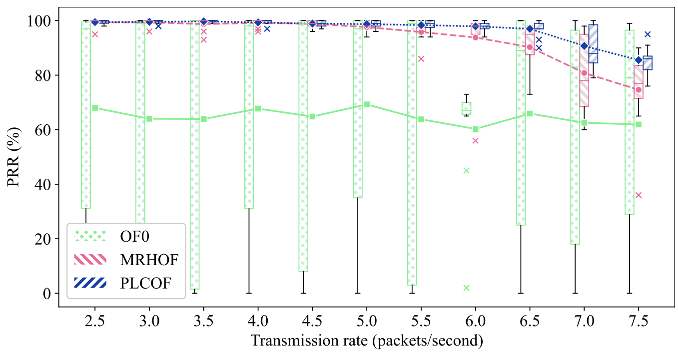


Fig. 10. PRR of each node (average and error bar) for the three OFs with varying data rates.

B. Evaluation Results

Routing topology: Fig. 8 shows a snapshot of routing topology constructed by MRHOF and *PLC-OF* during the experiments. OF0's topology was already shown in Fig. 5a. First, it is observed that nodes 23, 24, 33 and 34, those connected to SEPA filter (Fig. 3), could not reach the root directly. Secondly, the depth of the topologies is more or less similar. In general, however, *PLC-OF* has slightly more nodes deeper in the tree owing to the application of diversity in the metric.

Reliability: Fig. 9 plots the PRR of each node for the three OFs under 7.5 pkts/s data generation rate. Fig. 9 indicates that *PLC-OF* attained higher and fairer PRR than other OFs. In the case of OF0, some nodes were unable to deliver any message (0%) because of link asymmetry.

Fig. 10 presents PRR error bar (over 11 nodes) for each OF with varying data generation rates. Both *PLC-OF* and MRHOF ensure approximately 99% PRR under low data rate until reaching 5 pkts/s. However, when the transmission rate is increased beyond that, the results differ distinctly. *PLC-OF* can hold data rate of up to 6.5 pkts/s. If the rate is increased further, the PRR drops much slower than MRHOF. This is because PHY layer diversity responds and adapts more promptly than link layer ETX. In all, *PLC-OF* served higher data rate communication than ETX-based MRHOF over PLC.

Channel usage: Both PHY layer diversity and link layer retransmissions affect the amount of channel occupancy required for a message delivery. Smaller channel usage connotes that the network can achieve higher efficiency in terms of achievable throughput, energy usage, and scalability. To concisely compare relative channel usage of the three OFs, we multiplied the number of transmissions with corresponding diversity for each frame which would represent the number of identical frames repeated for a message delivery [4].

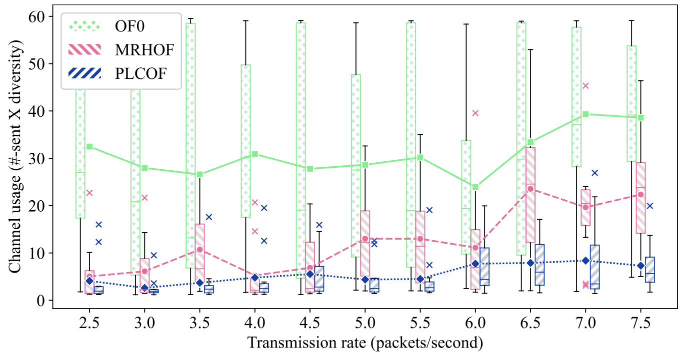


Fig. 11. Relative channel usage of each node (average and error bar) for the three OFs with varying data rates.

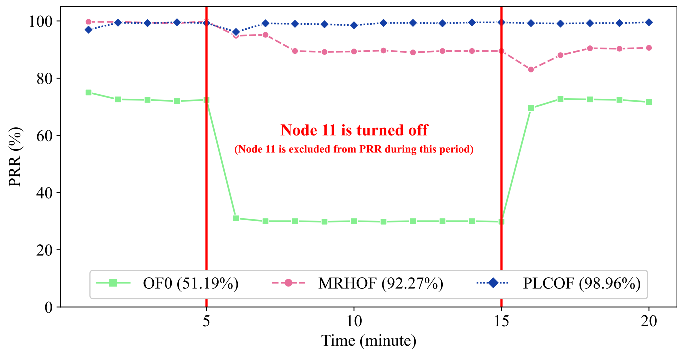


Fig. 12. Node failure scenario: Average PRR of all active nodes when node 11 was turned off/on during the experiment.

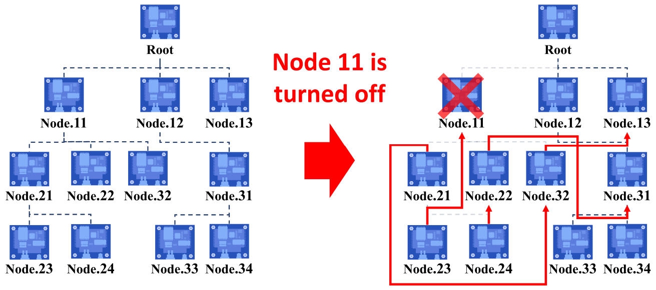
The results in Fig. 11 revealed that, while the overall channel usage worsens as data rate increases owing to packet losses and retransmissions, *PLC-OF*'s channel usage is significantly lower than that of other OFs. This is because *PLC-OF* considers ETX and diversity when it finds the routes. If *PLC-OF* chooses slightly longer paths on average, it reduces entire channel usage by reducing retransmissions and repetitions. Consequently, *PLC-OF* only uses one third of the channel under highest data rate compared to MRHOF.

Robustness to node failure: Low-cost embedded devices may run out of battery or physically break in real-world IoT applications. Some links may fail, for example, because of severe noise generated by power-consuming electronic appliances. Thus, it is expedient for network nodes to find alternative routes for robustness and reliability.

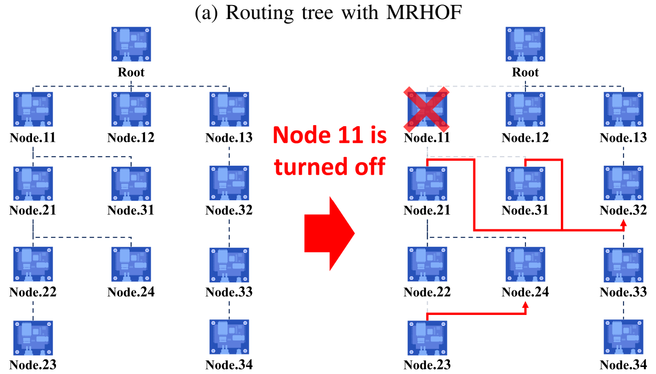
We switch off a node in the middle of the topology during a data collection to investigate how the three RPL OFs respond to node failure. Specifically, while collecting data from all nodes at 1 pkt/s data rate on the same topology as the previous experiment (Fig. 8 and 5a), we powered off node 11 at five minutes into the experiment, for ten minutes, and turned it back on.

Fig. 12 plots the average per-minute PRR of the three OFs

[4]We ignore PHY header and preamble size because they are under 10 bytes while the repeated PHY payload is 360 bytes each.



(a) Routing tree with MRHOF



(b) Routing tree with *PLC-OF*

Fig. 13. Node failure scenario: Routing topology change of each OF when node 11 was turned off during the experiment.

for all active nodes in the node failure scenario. Thus, we exclude node 11 from PRR calculation when node 11 is turned off. It indicates that, except for the first minute ($t = 6$ min), *PLC-OF* maintains almost 100% PRR despite the switch off of a node in the middle of the topology. Conversely, MRHOF lost approximately 10–15% of PRR and did not recover quickly after node 11 was turned on. OF0 was impacted more with PRR dropping by approximately 40%. Overall average PRR over the entire period (20 min) was 98.6% for *PLC-OF*, 92.27% for MRHOF, and 51.19% for OF0.

To understand the reason behind this, Fig. 13 illustrates the routing topology change of each OF when node 11 was turned off. With MRHOF (Fig. 13a), node 23 connects to node 11 although node 11 off. This is because the cost variation of MRHOF is small and responds slowly to transmission failures. Before node 11 was turned off, node 23 was connected to node 21 and its cost was approximately 4 ($\approx$3 for path ETX, $\approx$1 for link ETX). Thus, link quality to node 21 was sufficiently better than to node 11. However, when node 11 was turned off, node 21 detected it and became node 32's child. Node 21's path cost increased accordingly. The cost of node 21's route became larger than the last information received from node 11 (before it was turned off); thus, node 23 changed its parent to node 11. Consequently, several routes were incorrect until node 11 was removed from the routing table via timeout for MRHOF. When node 11 was turned on again, node 23 did not recover connectivity quickly because node 21 did not return to being node 11's child as depicted in Fig. 13a. In node 21's perspective, the route through node 11 is not attractive in terms of total cost compared to its current path because it miscalculates the quality of node 11 link as too poor from

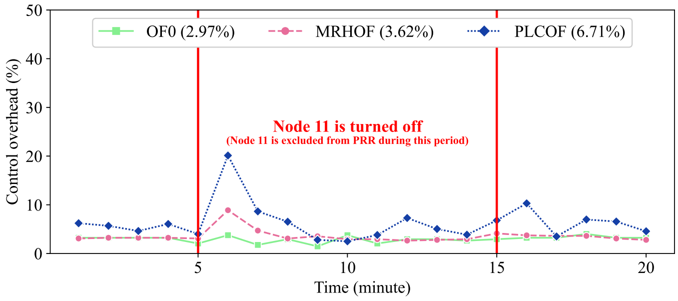


Fig. 14. Node failure scenario: Control overhead (# control packets / # total packets) when node 11 was turned off/on during the experiment.

the recent-past transmission failures. This phenomenon is even worse with OF0 because the OF0's path change mechanism is more defensive than that of MRHOF.

Conversely, all *PLC-OF* nodes successfully moved to other subtrees as shown in Fig. 13b. Multiplication of diversity and ETX in *PLC-OF* enables the network to update their cost and bypass routes quickly when link quality becomes worse. Therefore, *PLC-OF* had only a slight impact while having significantly better reliability.

Control overhead: RPL uses DIO (DODAG information object) / DAO (DODAG advertisement object) / DIS (DODAG information solicitation) route control messages to build a DODAG (destination oriented directed acyclic graph) formed network topology. From the application's perspective, these are control overheads in the network. The frequency of these messages is governed by the standard Tickle timer [33] such that overhead is low when the network is stable (that is,. no changes); however, it is high when the network needs to adapt to dynamics and resolve inconsistencies.

To examine how much control overhead each OF generates, Fig. 14 plots the average per-minute control overhead of each OF during the node failure scenario. Although *PLC-OF* has a slightly higher overhead than other OFs, the overall values are low and the differences are small. When node 11's state changes (OFF at 5 min, ON at 15 min), *PLC-OF* quickly detects network inconsistency and exchanges more control messages than other OFs instantly to find alternative paths.

However, this is not a problem for the following reasons. First, *PLC-OF* generates more control messages to achieve significantly better reliability (PRR). Considering the amount of received data or number of end-to-end retransmissions required to recover the losses, the added overhead is negligible. Additionally, energy efficiency is not as critical in PLC as wireless because all devices are connected to wall-power; we can relax energy requirement for improved reliability. Furthermore, the actual energy usage could be less in spite of more control messages because *PLC-OF* uses links with lower diversity and ETX, resulting in lower overall channel usage as shown in Fig. 11.

The experimental results reveal that *PLC-OF* can achieve better RPL performance in terms of 1) reliability under higher data rate, 2) channel occupancy during data delivery, and 3) robustness to network failure with minimal added overhead.

V. Conclusion

PLC-OF is a novel objective function designed specifically for multihop PLC networks. We were motivated by the fact that existing OFs in RPL exhibit inferior performances that are not applicable in real-world IoT-PLC networks. The results of preliminary studies support the hypothesis by showing the PLC's asymmetric and time varying characteristics. To achieve efficient channel utilization and reliability, we adopted PLC PHY's *diversity* into link and path metric, together with ETX and load balancing, to reflect the unique characteristics of PLC. Through evaluations on real PLC testbed with 12 devices, we have shown that *PLC-OF* can find better routes and enhance performance with simple and effective ideas compared to standard RPL. Particularly, *PLC-OF* can support higher data rates that could be required in industrial applications such as smart factories and in-vehicle networks. We believe our work is a key solution for future IoT-PLC systems, and we plan to apply it in larger-scale real smartgrid AMI deployments in future studies.

References

[1] B. L. Risteska Stojkoska and K. V. Trivodaliev, "A review of Internet of things for smart home: Challenges and solutions," *J. Cleaner Production*, vol. 140, pp. 1454–1464, Jan. 2017.

[2] Z. Fan, *et al.*, "Smart grid communications: Overview of research challenges, solutions, and standardization activities," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 1, pp. 21–38, 2013.

[3] M. B. Ali, W. Endemann, and R. Kays, "Propagation loss model for neighborhood area networks in smart grids," *J. Commun. Networks*, vol. 24, no. 3, pp. 313–323, Jun. 2022.

[4] T. Miyake, M. Lürkens, S. Chandra, C. Cheng, and J.-P. Faure, "Smart city and streetlight case studies using IEEE 1901 high-speed powerline communication," IEEE SA and HD-PLC Alliance, Feb. 2022.

[5] S. Galli, A. Scaglione, and Z. Wang, "For the grid and through the grid: The role of power line communications in the smart grid," *Proc. IEEE*, vol. 99, no. 6, pp. 998–1027, Jun. 2011.

[6] G. López *et al.*, "The role of power line communications in the smart grid revisited: Applications, challenges, and research initiatives," *IEEE Access*, vol. 7, pp. 117 346–117 368, Jul. 2019.

[7] R. Alexander *et al.*, "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks," RFC 6550, Mar. 2012. [Online]. Available: https://rfc-editor.org/rfc/rfc6550.txt

[8] H.-S. Kim, J. Ko, D. E. Culler, and J. Paek, "Challenging the IPv6 routing protocol for low-power and lossy networks (RPL): A survey," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2502–2525, Sep. 2017.

[9] P. Thubert, "Objective function zero for the routing protocol for low-power and lossy networks (RPL)," RFC 6552, Mar. 2012. [Online]. Available: https://rfc-editor.org/rfc/rfc6552.txt

[10] D. Barthel, J. Vasseur, K. Pister, M. Kim, and N. Dejean, "Routing metrics used for path calculation in low-power and lossy networks," RFC 6551, Mar. 2012. [Online]. Available: https://rfc-editor.org/rfc/rfc6551.txt

[11] O. Gnawali and P. Levis, "The minimum rank with hysteresis objective function," RFC 6719, Sep. 2012. [Online]. Available: https://rfc-editor.org/rfc/rfc6719.txt

[12] H.-S. Kim, H. Kim, J. Paek, and S. Bahk, "Load balancing under heavy traffic in RPL routing protocol for low power and lossy networks," *IEEE Trans. Mobile Comput.*, vol. 16, no. 4, pp. 964–979, Apr. 2017.

[13] E. Aljarrah, "Deployment of multi-fuzzy model based routing in RPL to support efficient IoT," *Int. J. Commun. Netw. Inform. Security*, vol. 9, no. 3, pp. 457–465, Dec. 2017.

[14] P. Sanmartin *et al.*, "Sigma routing metric for RPL protocol," *Sensors*, vol. 18, no. 4, p. 1277, Mar. 2018.

[15] H.-S. Kim, J. Paek, D. E. Culler, and S. Bahk, "PC-RPL: Joint control of routing topology and transmission power in real low-power lossy network," *ACM Trans. Sensor Netw.*, vol. 16, no. 2, pp. 1–32, May 2019.

[16] H.-S. Kim, J. Paek, and S. Bahk, "RPLIE: RPL for indoor environments under midterm link fluctuations," *J. Commun. Networks*, vol. 23, no. 3, pp. 201–211, Jun. 2021.

[17] "Telecommunications and information exchange between systems - Powerline communication (PLC) - High speed PLC medium access control (MAC) and physical layer (PHY) - Part 1: General requirements," International Organization for Standardization and International Electrotechnical Commission," Standard, Jul. 2009.

[18] CNU GLOBAL, "Power Line Communication Device Speficiation," Available at http://www.cnuglobal.com/sub/sub02_03.php?cat_no=6.

[19] O. Gnawali and P. Levis, "The ETX objective function for RPL," *draft-gnawali-roll-etxof-01*, May 2010.

[20] Y. M. Chung, "Overview and characteristics of IoT PLC," in *Proc. IEEE ICEIC*, 2020.

[21] C. Chauvenet, B. Tourancheau, D. Genon-Catalot, P.-E. Goudet, and M. Pouillot, "A communication stack over PLC for multi physical layer IPv6 Networking," in *Proc. IEEE SmartGridComm*, 2010.

[22] C. Chauvenet, B. Tourancheau, and D. Genon-Catalot, "802.15.4, a MAC layer solution for PLC," in *Proc. ACS/IEEE AICCSA*, 2010.

[23] Cisco, "Connected grid networks for smart grid - Field area network," http://www.cisco.com/web/strategy/energy/field_area_network.html.

[24] D. S. J. D. Couto, D. Aguayo, J. Bicket, and R. Morris, "A high-throughput path metric for multi-hop wireless routing," in *Proc. ACM MobiCom*, 2003.

[25] P. Karkazis *et al.*, "Design of primary and composite routing metrics for RPL-compliant wireless sensor networks," in *Proc. TEMU*, Jul. 2012.

[26] O. Gaddour, A. Koubaa, N. Baccour, and M. Abid, "OF-FL: QoS-aware fuzzy logic objective function for the RPL routing protocol," in *Proc. WiOpt*, May 2014.

[27] F. Lemercier and N. Montavont, "Performance evaluation of a rpl hybrid objective function for the smart grid network," in *Proc. AdHoc-Now*, 2018.

[28] S. A. Abdel Hakeem, A. A. Hady, and H. Kim, "RPL routing protocol performance in smart grid applications based wireless sensors: Experimental and simulated analysis," *Electronics*, vol. 8, no. 2, p. 186, Feb. 2019.

[29] F. Ye, L. Zhao, C. Jiang, and J. Sun, "A dual-mode communication power internet of things routing algorithm based on rpl protocol," in *Proc. IOP Conference Series: Materials Science and Engineering*, 2020, p. 072078.

[30] J. W. Hui, W. Hong, J. Paek, and P. Buonadonna, "Distributed node migration between routing domains," Feb. 2017, US Patent 9,565,108.

[31] Y. H. Cho and J. D. Lee, "Assistant device for removing elecromagnetic waves," Sep. 1997, KR Patent 10-0274928.

[32] G. Montenegro, J. Hui, D. Culler, and N. Kushalnagar, "Transmission of IPv6 Packets over IEEE 802.15.4 Networks," RFC 4944, Sept. 2007. [Online]. Available: https://rfc-editor.org/rfc/rfc4944.txt

[33] P. Levis, N. Patel, D. Culler, and S. Shenker, "Trickle: A self-regulating algorithm for code propagation and maintenance in wireless sensor networks," in *Proc. USENIX NSDI*, Mar. 2004.

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