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Bringing life out of diversity: Boosting network lifetime using multi-PHY routing in RPL

Mina Rady^{1,2} Quentin Lampin¹ Dominique Barthel¹ Thomas Watteyne²

¹ Massive IoT Connectivity Team, Orange

² Innovation, Meylan, France

Abstract

In this article, we propose a routing mechanism based on the RPL protocol in a wireless network that is equipped with a mix of short-range and long-range radios. We introduce Life-OF, an objective function for RPL which uses a combination of metrics and the diverse physical layers to boost the network's lifetime. We evaluate the performance of Life-OF compared to the classical MRHOF objective function in simulations. Two key performance indicators (KPIs) are reported: network lifetime and network latency. Results demonstrate that MRHOF tends to converge to a pure long-range network, leading to short network lifetime. However, Life-OF improves network lifetime by continuously adapting the routing topology to favor routing over nodes with longest remaining lifetime. Life-OF combines diverse radios and balances power consumption in the network. This way, nodes switch between using their short-range radio to improve their own battery lifetime and using their long-range radio to avoid routers that are close to depletion. Results show that using Life-OF improves the lifetime of the network by up to 470% that of MRHOF, while maintaining similar latency.

1 | INTRODUCTION

Applications of the Internet of Things (IoT) have been pervasive in commercial use-cases where wireless connectivity is needed. These include environmental monitoring,¹ smart building,^{2,3} precision agriculture,⁴ automated meter reading,⁵ indoor localization,⁶ micro-robot connectivity,⁷ smart grid management⁸ and predictive maintenance.⁹ In such use-cases, an area is covered with a wireless mesh of battery-powered devices where mains power is not available. Even when mains power is available, a non-invasive deployment is often inevitable in sensitive infrastructures (e.g., hospitals,⁶ complex industrial plants⁹). This creates a need to manage the network protocol in such a way as to result in the longest battery lifetime possible.

Several wireless technologies have been introduced to save the average battery lifetime in a network by using energy efficient modulations and protocols: such as SmartMesh IP and Zigbee. Such technologies rely on the classical short-range radio at 250 kbps in the 2.4 GHz band as defined by IEEE 802.15.4 (2003) standard. They improve the average battery lifetime in the network by using medium access control (MAC) techniques that allow the radios to go into sleep mode when they are not needed.

However, in several use cases, optimizing for energy saving alone does not necessarily mean optimizing for network cost.¹⁰ In some cases, replacement of batteries requires sending a hired employee to replace the batteries and therefore the employee hourly salary is spent on battery replacement. This leads to a situation where the cost of the actual batteries is

negligible compared to the cost of battery replacement. In this case, the real cost of running the network can be expressed as the number of trips an employee has to make to replace a battery (regardless whether it is for one device or all the devices). For instance, a network can have 90% of its motes living for 5 years with 10% of the motes that die after 6 months. In this case, the real cost of running the network is the cost of one factory-trip per 6 months. However, if 100% of the nodes have a 2-year battery lifetime, the effective cost of running the network is one factory trip every 2 years. The latter scenario is more budget-efficient, even if it has an overall lower average battery lifetime. We then define the “network lifetime” as the time from the start of network until the *first* mote runs out of battery energy.

It is worth noting that some networks can be built with redundancy in mind such that the network can still be reliable even when 10%–15% of the motes have lost their battery power. Even in this case, optimizing for time to first death is relevant since the load balancing across different nodes helps improve the lifetime of the nodes that are more likely to be depleted first (even the redundant ones). Therefore, we consider optimization for time to first death as an orthogonal approach to network redundancy since time to first death helps improving maintenance cost, but network redundancy helps improving network reliability in case of failure.

The Internet Engineering Task Force (IETF) runs several working groups that standardize protocols to enable energy efficient IoT. One of these working groups is Routing Over Low power and Lossy networks (ROLL) focused on the routing layer in IoT applications. The group standardized RPL: the IPv6 Routing Protocol for LLNs (low-power and lossy networks, otherwise known as the IoT mesh networks).¹¹ RPL provides an elaborate framework with a wide range of features that enable it to serve basic as well as complex use cases. A key advantage of RPL is that it is a distributed protocol: decisions are taken independently by each node. This way, it minimizes the risk of having a single point of failure, such as when the network is managed by a centralized controller (i.e., path computation element). It also reduces the network control overhead as nodes do not send all their state information to the controller. The core routing decision in RPL is taken by the objective function (OF) which evaluates each available path according to “an objective” and decides which path best meets that objective. There are currently two IETF-standardized OFs that aim to improve latency and energy by choosing paths with the least possible number of hops or transmissions.

Furthermore, a wide range of physical layers have been introduced to the IoT market to serve both long-range and short-range applications as they vary in the type of modulation they use, the frequency band, and bitrate. We refer to a combination of modulation, frequency band and bitrate as “PHY”. Subsequently, IEEE802.15.4 (2003) standard was later amended by IEEE802.15.4g (2012) which defines 31 PHYs for Smart Utility Network (SUN) applications. They are based on three families of modulations: frequency shift keying (FSK), offset quadrature phase-shift keying (O-QPSK), and orthogonal frequency division multiplexing (OFDM). Data rates range from 25 kbps to 800 kbps. Two frequency bands are used: 2.4 GHz and sub-GHz.

In this article, we propose an OF that improves network lifetime using dynamically calculated metrics and using a heterogeneous physical layer. We call it the lifetime objective function, “Life-OF”. When using this OF, the network alternates between two kinds of connectivity: (1) a node uses short-range PHYs to save its own energy (while consuming more energy from neighbors); (2) it uses long range PHYs, thereby saving the energy of its neighbors. The result is that the network re-routes traffic to avoid relay nodes that are close to full depletion. We demonstrate the performance of this OF by simulating nodes that are equipped with radios that vary in link-budget, bitrate, frequency band, and power consumption. Specifically, we use the following PHYs: FSK 868 MHz as the slowest bitrate PHY, OFDM 868 MHz as the fastest bitrate PHY, the canonical O-QPSK 2.4 GHz as an in-between option.

The remainder of this article is organized as follows. Section 2 presents the related work in both standardization and research venues. Section 3 defines the problem statement and presents the specific contributions of the article. Section 4 outlines the components of the routing algorithm for Life-OF. Section 5 outlines the methodology for the performance evaluation of the OF. Section 6 presents the simulation results. Finally, Section 7 presents the conclusion and the future work.

2 | RELATED WORK

This section presents previous work related to this research. We organize the related work into three categories: First, RPL standardization (Section 2.1) which introduces a background on the RPL standard and related Requests For Comments (RFCs). Second, OFs for a hybrid RPL topology (Section 2.2) which introduces related work on RPL OFs that intersect with this work. Third, multi-PHY integration (Section 2.3) which introduces related work on integrating diverse PHYs in a single protocol stack.

2.1 | RPL standardization

RPL was first standardized in 2012 as a proactive, distance-vector, distributed routing algorithm, aligned on Destination Oriented DAGs rooted at the internet border routers.¹¹ It was later extended with options to do point-to-point proactive routing, and to do reactive routing. It is currently being extended to enable centralized routing.

The Root advertises metrics¹² that are used by intermediate nodes to select routes according to the OF. Standardized OFs include route selection by hop-count (called OF0¹³) or by minimum end-to-end ETX with hysteresis (called MRHOF). The network DODAG is guaranteed to be acyclic (in steady state) by having each node assign itself and advertise a rank that is strictly monotonic along any path to the Root. In addition to defining how routes are selected, the OF also specifies how the rank is calculated. The RPL protocol is extensible with other objective functions, yet to be defined. The currently defined metrics include node metrics such as: node remaining energy, node workload, or hop-count. Link metrics are also defined, for example, link throughput, latency, reliability, or link color.

Metrics are shared in the network via destination information object (DIO) multicasts. DIOs contain DAG metric containers (DMCs) which describe the utilized metrics and how they are shared in the network. We note two particular control points in the routing metric flag field that define how metrics are shared (which will be referred to later in the article).

- “R-Flag”: if set, the metric is recorded in a separate entry for each node along the path. Otherwise, the metric is aggregated along the path as one entry.
- “A-Field”: in case an aggregate metric is defined (i.e., R-Flag set to 0). It allows choosing the mode of aggregation: additive, minimum, maximum, or multiplicative.

This way, metrics can be combined in different ways to optimize the routing topology for different use-cases.

2.2 | OFs for a hybrid RPL topology

The main RPL standard RFC 6550¹¹ does not specify an OF for a RPL implementation. Specification of the OF is left to the architects of each network since the criteria of optimization can vary by use-case: some applications using alarms may prioritize delay over energy savings, other applications for utility metering in remote areas may prioritize energy saving over delay. Extensions to the standard have proposed OFs that can serve as reference points for RPL implementations. RFC 6552¹³ introduces OF0, which serves as a minimal OF that allows basic interoperation of RPL implementations in simple use cases. It uses the hop-count as an additive aggregate metric along the path. A major drawback is that nodes closer to the root in the routing tree will be selected as parents, irrespective of the link quality.

RFC 6719¹⁴ introduces the minimum rank with hysteresis objective function (MRHOF). It goes one step further than OF0 by using as a path metric the accumulated expected transmission count (ETX) of the links belonging to that path. However, doing this, it can be sensitive to temporary fluctuations in link quality across the path due to interference or multi-path fading.

Ben Saad et al. propose a heterogeneous infrastructure for IPv6 using a combination of diverse PHYs: power line communications (PLC) interface, sub-GHz radio at 250 kbps, and 2.4 GHz radio at 250 kbps.¹⁵ Authors proposed an infrastructure where PLC-RF routers are introduced to improve lifetime of an RF network. Authors emulate a testbed of 25 RF motes in a 50×50 m² area with a fixed RF range of 10 m and placed in a grid topology. Authors place mains-powered RF-PLC routers in optimal points and show how it leads to improvement of network lifetime.

Lemercier et al.^{16,17} address the challenge of routing when each node is equipped with heterogeneous interfaces, namely IEEE 802.15.4g RF and PLC. Authors compare three approaches for multi-PHY routing in RPL: a multi instance RPL - where RPL maintains a separate DODAG per each PHY, a parent-oriented design - where switching between PHYs is more favorable for interfaces of the same neighbor node, and an interface-oriented design - where each combination of node/interface is considered as an independent neighbor. The objective of the study is to arrive at a solution that yields the best network reliability in case of interface failure. This is expressed as the number of parent changes and degree of connectivity of the resulting topologies. Authors propose an OF that aims at optimizing the link quality and expected transmission time. They show that the parent-oriented design yields networks with the best reliability performance in terms of number of parent changes and link quality in the DODAG.

Iova et al¹⁸ propose an OF for RPL that optimizes for network lifetime. They propose that the routing algorithm avoids nodes that appear as energy bottlenecks. They also propose to use multi-parent routing to balance the load across the network. Their OF defines an expected lifetime node metric that is based on: node energy consumption, remaining battery energy, ETX, and estimated node traffic rate. They simulate the performance of the proposed multipath routing technique in single-PHY topologies of 30-90 nodes in a $300 \times 300 \text{ m}^2$. They show that the hybrid OF with probabilistic multipath routing is able to improve network lifetime by several orders of magnitude (depending on the network's density).

The work presented in this section demonstrates significant advances in adapting RPL for multi-PHY integration or network lifetime. Both OF0 and MRHOF offer a basic, PHY-agnostic, routing approach that leaves room for improvement in the case of multi-PHY networks or specialized use-cases. Ben Saad et al. demonstrate how introducing heterogeneous mains-powered routers can improve network lifetime. This confirms the intuition of the benefit of having heterogeneous network for improving lifetime. Lemercier et al. demonstrate that having a heterogeneous network with mix of wired/wireless interfaces can improve network reliability and stability. Our work goes a step further in this direction by demonstrating how heterogeneous nodes that are fully wireless and fully battery powered can improve network lifetime by integrating a mix of long-range and short-range PHYs. Iova et al. demonstrate the benefit of optimizing for a node's estimated lifetime to yield an energy balanced network with improved lifetime. This confirms the intuition behind using combined metrics for network lifetime optimization and how that path diversity can allow improving the network's lifetime. This article goes a step further by demonstrating an OF that makes use of heterogeneous PHYs to improve the network lifetime and how the characteristics of each PHY can be taken into account by the routing layer. Finally, this work simulates the resulting networks in a setting of 100 nodes in $2 \times 2 \text{ km}^2$. This is to demonstrate the potential impact of this function in wide area coverage.

2.3 | Multi-PHY integration

This section describes the most recent advances in multi-PHY networking for industrial applications. In a previous study,¹⁹ we evaluated the performance of a 6TiSCH network on top of different PHYs. 6TiSCH stands for IPv6 on the TSCH mode of the IEEE 802.15.4e standard. It is the adopted IETF protocol stack which enables wire-like reliability for industrial wireless mesh networks. It uses the canonical IEEE 802.15.4 O-QPSK 2.4 GHz at the PHY layer and RPL at the routing layer. The article adapts 6TiSCH to work on top of three different PHYs: FSK 868 MHz at 50 kbps as slowest bitrate PHY, OFDM 868 MHz at 800 kbps as fastest bitrate PHY, and O-QPSK 2.4 GHz at 250 kbps as an in-between option. The article proposes a principle of “no free lunch” as it shows that each PHY yields improved performance of 6TiSCH in some Key Performance Indicators (KPIs) at the cost of lower performance in other aspects. For example, using FSK 868 MHz yields the shortest end-to-end latency yet with lowest battery lifetime, which is the opposite of O-QPSK 2.4 GHz. The study makes the argument for the potential benefit from integrating diverse PHYs in one architecture. This way, the network can combine their benefits, which serves as a foundation for this article.

In a following study, we introduced the Generalized 6TiSCH (g6TiSCH) architecture for agile multi-PHY wireless networking.²⁰ It generalizes the 6TiSCH stack such that it can integrate any mix of diverse PHYs. It demonstrates that a multi-PHY network can offer a balanced performance that harnesses advantages of long-range and short-range PHYs. It showed better network latency and formation time and same lifetime and reliability as a pure long-range network.

The study by Brachmann et al²¹ introduces multi-PHY integration in the 6TiSCH stack. Authors choose two PHYs in the sub-GHz band for integration in the 6TiSCH MAC layer: 2-GFSK at 1.2 kbps for transmitting Enhanced Beacons (EB), 4-GFSK at 1000 kbps for data traffic. Experiments show that using the fast bitrate 4-GFSK at 1000 kbps for data packets decreases the probability of collision. This way, it leads to less than 0.1% channel utilization despite the higher re-transmission rate. Additionally, using the slow bitrate 2-GFSK at 1.2 kbps causes higher channel occupancy, at 2% duty cycle, while yielding faster network synchronization.

The proposal by Van Leemput et al²² introduces multi-PHY integration in TSCH networking. The authors propose to leverage slower PHYs for unicast links when the Received Signal Strength Indicator (RSSI) remains below a specific threshold. PHY adaptation takes place at the MAC layer by continuously assessing the link's RSSI. The resulting architecture demonstrates that a link throughput can be increased by 153% with only 84% power consumption. This is achieved by using single acknowledgment for multiple packets in the same slot.

The studies presented in this section demonstrate the untapped potential of multi-PHY wireless networking. First, the research by Brachmann et al²¹ demonstrates how a network can achieve energy efficiency for data packets and fast network synchronization by mixing both short and long range PHYs. We go one step further by demonstrating how diverse

PHYs can be used for routing data packets to improve network lifetime. Second, the research by Van Leemput et al²² demonstrates the benefits of using diverse PHYs at the MAC layer for re-transmission to improve network throughput. We go a step further by proposing to implement the multi-PHY management at the routing layer. We further show how the PHY characteristics are exposed to the routing layer to help it specifically improve the network lifetime. Finally, the g6TiSCH architecture²⁰ at its current state uses a simple weighted ETX OF that results into the same lifetime of a pure long range network using MRHOF. This study goes one step further by proposing a new OF, Life-OF, that extends network lifetime to be 470% that of a pure long range network using MRHOF.

3 | PROBLEM STATEMENT AND CONTRIBUTIONS

Previous research on the optimization of LPWAN architectures has demonstrated that optimizing for energy consumption in the network may not necessarily result in lower network costs.¹⁰ An example of this is the case where the cost of battery replacement is fixed whether it is for one mote or for the entire network. This cost reflects the paid-time of staff members to collect all the nodes, drive to the manufacturer and have all their batteries replaced. Therefore, this cost is incurred once the first mote has died, regardless how much energy was still remaining in the other motes.

Furthermore, availability of radio chips that support changing PHYs on a frame-by-frame basis can offer a chance to improve network lifetime. First, if a node has remaining lifetime less than its surrounding routers, it can extend its own lifetime by switching to route its traffic using a more energy efficient PHY. Second, if a node has remaining lifetime that is higher than its surrounding routers, it can relieve the routers by using a longer range PHY to bypass them to reach the root directly (or to reach a point closer to the root).

Achieving this multi-PHY integration in RPL was identified in an IETF problem statement by Muñoz et al.²³ We demonstrated in the g6TiSCH architecture²⁰ how a simple adaptation to RPL for multi-PHY integration can provide a balanced network performance. This research aims at going one step further by proposing an OF that optimizes for network lifetime while harnessing the advantages of heterogeneous PHYs.

Specifically, the contribution of this article is three-fold:

- We propose Life-OF: an OF for RPL that improves network lifetime using a heterogeneous physical layer.
- We evaluate the performance of Life-OF using simulations in long-range industrial scenarios and we compare its performance against MRHOF in a single-PHY setting and in a multi-PHY setting.
- We demonstrate that using Life-OF in a multi-PHY network leads to the best network lifetime while maintaining reasonable latency compared to MRHOF.

4 | THE ROUTING ALGORITHM

This section outlines the adaptations necessary for RPL to optimize for network lifetime. The adaptations to RPL to integrate Life-OF consist of four main components:

- Path evaluation and selection (i.e, the objective function).
- Node remaining lifetime evaluation.
- New rank calculation.
- Definition of RPL protocol elements to enable Life-OF.

Figure 1 is a high-level diagram that shows how the components interact with one another in a closed loop. The component for evaluating the node's remaining lifetime keeps track of the duty cycles for the different PHYs for a certain period.

The "path evaluation and selection" component keeps track of the current node's rank and the advertised ranks of each neighbor. Based on Life-OF, it selects the path with the best estimated path metric. At the beginning of a defined period (i.e., an epoch), the "node remaining lifetime evaluation" component estimates the node's lifetime based on the

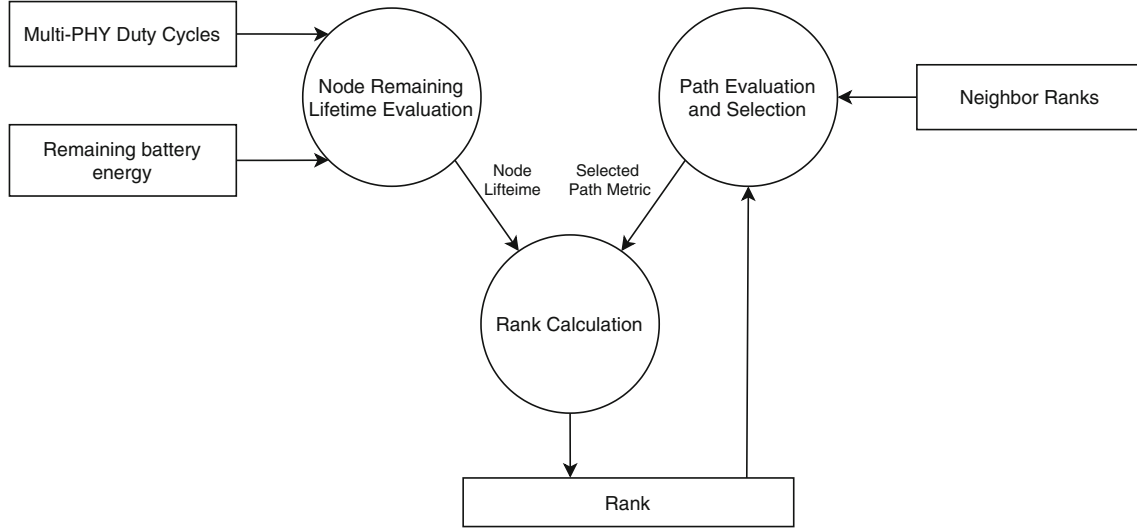


FIGURE 1 A logical diagram of interaction between the components of the Life-OF

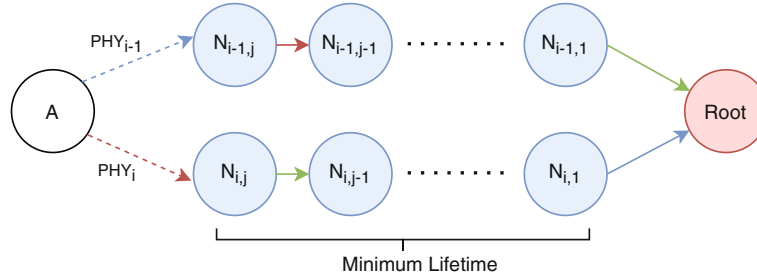


FIGURE 2 Example topology for illustration

usage of each PHY, its power consumption, and the remaining battery energy. Whenever there is a new lifetime estimation or a newly selected path, the node's rank is calculated by the “rank calculation” component.

The remainder of this section describes the behavior of each component.

4.1 | Path evaluation

This section describes how a node evaluates a cost for each neighbor and how it selects a path to the root. We consider a neighbor to be a combination of node and PHY layer. Each neighbor i has a self-computed rank: $Rank_i$. Each PHY_i has a designated weight that corresponds to its expected power consumption. We refer to this as weighted ETX noted $WETX(PHY_i)$.

We define a function that estimates a cost for each neighbor i based on $Rank_i$ and $WETX(PHY_i)$. The objective is to select the neighbor with the *least* cost among the available neighbors. We illustrate in Figure 2 a scenario where node A is making a routing decision between paths through N_i and N_{i-1} . Let the whole network agree on a common set of PHYs: $\Phi = \{PHY^1, \dots, PHY^L\}$. Let node A have K neighbors and use PHY_i with neighbor i , with $PHY_i \in \Phi$.

To obtain the cost, $WETX(PHY_i)$ has to be derived at first as follows:

- Energy per bit (EPB) for all PHYs is obtained according to Equation (1), where I_i is the current consumption of the radio chip of PHY_i in amps, V_i is the voltage in volts, and the bitrate is in bps.
- $EnergyWeight(PHY_i)$ is obtained by normalizing the EPB of all the PHYs with respect to the PHY with the lowest EPB according to Equation (2).

- $ETX(PHY_i)$ is obtained according to Equation (3) where $numTx_i$ is the number of transmissions to neighbor i and $numAck_i$ is the number of received acknowledgments.
- $WETX(PHY_i)$ is then obtained as a function of $EnergyWeight(PHY_i)$ and $ETX(PHY_i)$ according to Equation (4)

$$Energy\ Per\ Bit(PHY_i) = \frac{I_i \times V_i}{Bitrate_i}, \quad (1)$$

$$Energy\ Weight(PHY_i) = \frac{Energy\ Per\ Bit(PHY_i)}{Min(Energy\ Per\ Bit(PHY_1, \dots, PHY_L))}, \quad (2)$$

$$ETX_i = \frac{numTx_i}{numAck_i}, \quad (3)$$

$$WETX(PHY_i) = EnergyWeight(PHY_i) \times ETX(PHY_i). \quad (4)$$

Finally, the cost of the path through a neighbor N_i is obtained according to Equation (5).

$$Cost(N_i) = \frac{Rank_i}{WETX(PHY_i)} + MinHopRankIncrease \quad (5)$$

Where:

- We define $Rank_i$ using a range of values from $[Rank_{min}, Rank_{max}]$, where $Rank_{min}$ is the best possible rank (i.e., the advertised rank of the root), and $Rank_{max}$ is the highest possible rank (ie, least preferable).
- $MinHopRankIncrease$ is a constant value to guarantee loop avoidance by ensuring that the rank decreases monotonically across any given path.

The reasoning behind the formulation in Equation (5) is as follows. $Rank_i$ expresses the rank of the neighbor, and therefore, the lower, the better. If both neighbor N_i and N_{i-1} have the same rank, then the neighbor with the PHY of lower energy weight will result into a lower rank, and therefore will be favored (Equations 4, 2, and 1). If both neighbors share the same rank and the same PHY, then the neighbor with the lower ETX (Equations 4 and 3) will be favored.

4.2 | Node lifetime estimation

Estimating the lifetime of a node is a key component, as a node metric and as a path metric as well. If a node has a low lifetime, it should favor higher bitrate PHYs for up-link and it should also be avoided by other nodes to be used as a router.

The remaining lifetime of a node can be estimated in two ways, depending on the available hardware. Some boards that are equipped with circuits that allow measuring the remaining battery charge. This allows keeping track of charge withdraw and subsequently estimating the remaining lifetime of the node. However, other boards may not have that circuitry in place and therefore cannot have that necessary information from the hardware. In our approach, we assume the scenario where this circuitry is not available and we demonstrate how a node can estimate its energy consumption and remaining battery energy. Therefore, the node's remaining lifetime is estimated by monitoring (1) the average power consumption of each PHY and (2) by estimating its remaining battery energy.

To estimate the average power consumption of L available PHYs, the node keeps track of the duty cycle of each PHY j in receive mode and in transmission. Based on the power characteristics of each PHY, the node can estimate the overall power consumption of the different PHYs. The average power consumption of A can be estimated according to Equation (6). Remaining battery energy is updated every epoch after a duration of ΔT and is estimated according to Equation (7).

The remaining node lifetime can be estimated based on the remaining battery energy according to Equation (8)

$$\begin{aligned} \text{Average Node Power Consumption}(A) = & \sum_{j=0}^L \text{Duty Cycle}_{rx}(PHY_j) \times I_{rx}(PHY_j) \times V(PHY_j) \\ & + \sum_{j=0}^L \text{Duty Cycle}_{tx}(PHY_j) \times I_{tx}(PHY_j) \times V(PHY_j), \end{aligned} \quad (6)$$

$$\text{Remaining Battery Energy} = \text{Latest Battery Energy} - (\text{Average Node Power Consumption} \times \Delta T), \quad (7)$$

$$\text{Lifetime} = \frac{\text{Remaining Battery Energy}}{\text{Average Node Power Consumption}}. \quad (8)$$

We are aware that there are different internal activities that can consume significant power compared to radio activities such as certain kinds of sensors or extensions to the node. Since this article is focused on the routing protocol on top of heterogeneous radios, we choose to assume negligible power consumption of nonradio components.

In the following subsection we explain how a node calculates its new rank.

4.3 | Node rank calculation

In a classical RPL OF such as MRHOF, the rank can be influenced by only one dynamic metric, which is the path ETX. In Life-OF, the rank of the node is influenced by three dynamic metrics: path lifetime, path hop-count, and path ETX. As illustrated in Figure 1, rank in Life-OF is recalculated in case one of two events take place: when there is new estimation of the lifetime of the node, or when the node makes a routing decision to select a certain neighbor for up-link.

In the first case, when there is new estimation of the lifetime of a node, the new rank Rank' is calculated as follows. Let node A (Figure 2) have a route through N_{i-1} . Assume the lifetime of node A (Figure 2) changes at an epoch, it obtains the following metrics:

- The path lifetime (years): defined as the minimum of the lifetimes of all the nodes in the path *except* the root *and* the node itself. We call this: $\text{Lifetime}(\overrightarrow{N_{i-1}})$.
- The path hop-count (hops): defined as the number of hops to the root. We call this: $\text{Hop Count}(\overrightarrow{N_{i-1}})$
- The energy weight of PHY_{i-1} : calculated as $\text{WETX}(\text{PHY}_{i-1})$ according to Equation (4).

Subsequently, the new rank Rank' is calculated using these metrics according to Equation (9).

$$\text{Rank}'(A) = \frac{-1 \times \text{Lifetime}(\overrightarrow{N_{i-1}}) \times 10^5}{\text{WETX}(\text{PHY}_{i-1})} + \text{Hop Count}(\overrightarrow{N_{i-1}}) \times \text{MinHopRankIncrease} \quad (9)$$

The reasoning behind this formulation is as follows. Lower rank indicates better position in the network and a better candidate for routing. Therefore, higher lifetime leads to lower rank as it is converted to a negative value. A scaling factor of 10^5 is used to increase sensitivity to path lifetime. Since $\text{Lifetime}(\overrightarrow{N_{i-1}})$ is expressed in years, a scaling factor of 10^5 allows expressing small lifetimes down to ≈ 10 hours without fractions. This way, it becomes easier to implement the OF in the computationally limited embedded devices without use of fractions. We consider that any lifetime below ≈ 10 hours is negligible. If the node is routing over a PHY with higher WETX, its advertised rank will be lower accordingly. This way, its attractiveness as a router decreases by a factor of WETX. Finally, adding the number of path hops makes nodes closer to the root (along the same path) more attractive as routers.

In the second case, if node A switches to a new path through neighbor N_i (while its own remaining lifetime has not changed), it calculates its new rank Rank' according to Equation (10). Then, Rank' , will be the new advertised rank for node A .

$$\text{Rank}'(A) = \text{Max} \left(\text{Rank}(A), \frac{\text{Rank}(N_i)}{\text{WETX}(\text{PHY}_i)} \right) + \text{WETX}(\text{PHY}_i) \times \text{MinHopRankIncrease}. \quad (10)$$

The reasoning behind this formulation is similar to the previous formulation. We note that the worse rank between the node and its parent is identified using the expression $\text{Max}(\text{Rank}(A), \text{Rank}(N_i)/\text{WETX}(\text{PHY}_i))$. This way, the node advertises the worst case scenario along its path. Finally, we add $\text{WETX}(\text{PHY}_i) \times \text{MinHopRankIncrease}$ to increase the attractiveness of nodes higher up the same path.

In the following subsection, we describe a specification within the RPL protocol to implement Life-OF.

TABLE 1 Specification of the DAG metric container

	Metric type	R-Flag	A-Field
Node lifetime	Node state and attribute object	0 (Aggregate)	2 (Minimum)
Hop count	Hop count object	0 (Aggregate)	0 (Additive)

4.4 | RPL protocol elements

To use Life-OF in RPL, we propose specifications within the RPL standard to enable it. First, we propose that the RPL DMCs contain three different metrics derived from the standard:¹² node lifetime, path hop-count, and link ETX. Table 1 outlines how each metric can be specified within the RPL standard and the relevant settings in the DMC flag field (as introduced in Section 2.1). We note that Life-OF only uses the link-level ETX metric and it does not need an accumulated path-level ETX metric.

Second, the execution of Life-OF should be triggered when the estimated node lifetime changes (in addition to normal triggers such as reception of DIOs). This additional trigger conforms to the Objective Function guidelines in RFC 65502.¹¹ It is important to choose a balanced duration of sampling the node's power consumption and remaining battery energy. On the one hand, the sampling duration should be long enough to provide reliable lifetime estimations and therefore stable routing decisions. On the other hand, it should not be too long that it prevents nodes from reacting fast enough when they are undergoing heavy power consumption.

5 | EVALUATION METHODOLOGY

Cooja is a commonly used by the research community to evaluate different objective functions proposed for RPL. It is an emulator for certain hardware architectures such as Zolertia Z1 mote and is used to emulate the execution of embedded firmware with full protocol stacks. It has been used in recent papers such as Ul Hassen et al²⁴ and Kniess and Marques.²⁵ In this article, we are interested in the high level performance of the RPL OF irrespective of the MAC layer or the firmware implementation. This way, introducing new OFs can be made simpler as the simulator is written in high level Python scripts rather than low level C code.

Therefore, to evaluate our approach, we developed a simple discrete time RPL Simulator (RPLSim) that is focused on mimicking the behavior of RPL in multi-PHY topologies. For the propagation loss model, we use the Pister-Hack trace-based propagation loss model recently utilized in other simulators.²⁶⁻²⁸ We tune the model for the sub-GHz PHYs to match the traces obtained from the range tests by Muñoz et al.¹ RPLSim allows simulating RPL topology convergence in a distributed network where nodes are equipped with multi-PHY interfaces with diverse bitrates, power-consumption, and link qualities. We refer to the power characteristics of the AT86RF215 radio chip by Atmel²⁹ for the Sub-GHz PHYs and the CC2538 radio chip by Texas Instruments³⁰ for the 2.4 GHz PHY (as used in previous research^{19,20,31}). The characteristics and the derived energy weights are outlined in Table 2. Furthermore, RPLSim estimates the power consumption of each node depending on its load and the link quality with each neighbor. This follows the same process for duty cycle estimation

TABLE 2 Characteristics of the simulated PHYs

	FSK 868 MHz	OFDM 868 MHz	O-QPSK 2.4 GHz
Radio chip	AT86RF215	AT86RF215	CC2538
Data rate	50 kbps	800 kbps	250 kbps
I_{TX}	62 mA	62 mA	24 mA
I_{RX}	28 mA	28 mA	20 mA
Supply voltage	2.5 V	2.5 V	3.0 V
Energy per bit	4.50 μ J	0.28 μ J	0.53 μ J
Energy weight ^a	16.00	1.00	1.89

^aNormalized as ratio to the PHY with the lowest energy per bit (ie, OFDM 868 MHz).

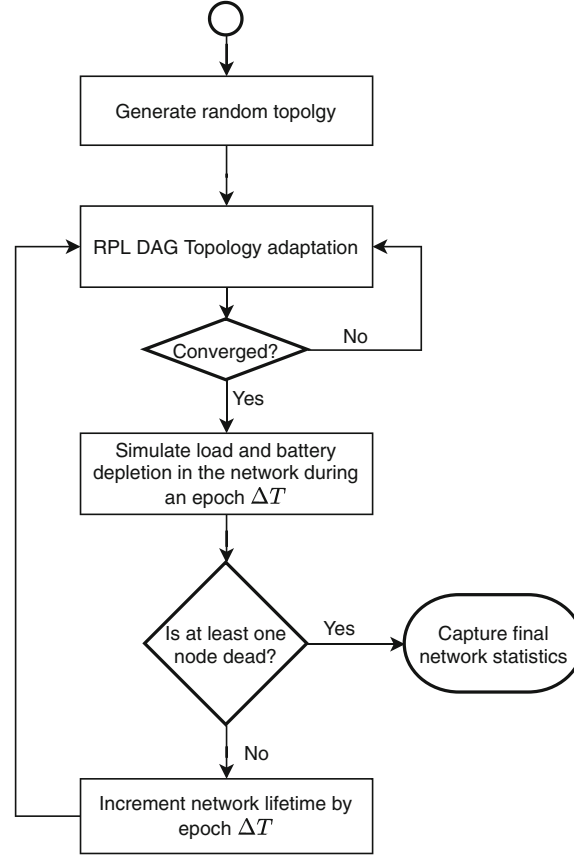


FIGURE 3 High level flow chart of RPLSim

as Iova et al.¹⁸ We extend it to use different power characteristics and bitrate for each neighbor depending on the used PHY. This allows to mimic the battery discharge for each node at each epoch. This way, we are able to observe how Life-OF adapts the routing topology at each epoch to optimize for the network's lifetime.

Figure 3 depicts a high level flowchart of RPLSim. At the beginning of a run, a random 2-dimensional topology is generated with specified number of nodes and square side length. After a topology is generated, the routing algorithm is run on nodes in the network in a random order until each node converges on a selected parent. Then the simulator estimates the duty cycle of each mote based on how many nodes use it as a router, the bitrate of the PHY of each neighbor, and ETX of each link. We assume a periodic traffic pattern where a node generates 4 frames per minute of 127 B each. Nodes are assumed to be equipped with 2 AA batteries with a total energy of 8.2 Wh. Then RPLSim mimics the decrease in battery remaining energy of each node until the next epoch. If all nodes are still alive, RPL is executed again on each node, and so forth. When at least one mote depletes all its battery, the simulation marks the end of the network lifetime. The discrete time resolution has been set as follows. The duration between epochs has been set to 6 months. Each two epochs, a small resolution epoch of 5 minutes is inserted to mimic network refresh.

We compare the performance of Life-OF and MRHOF in the same generated topologies. MRHOF is implemented based on its default configuration outlined in published RFCs.^{14,32} Any link with $ETX > 2$ is considered nonfunctional, so as to maintain a reasonably minimal network quality. The definitions used for the RPL constants for each OF are listed in Table 3. For Life-OF, we set $Rank_{min}$ to -10^5 so it can still express a severe case of a mote with remaining lifetime of 1 day that uses an FSK up-link with $ETX = 2$, without use of fractions (to simplify implementation in embedded devices). For the same reason, we set $Rank_{max}$ to -50 . The highest possible WETX is 32, which is the WETX of an FSK link with $ETX = 2$. Since the rank is divided by WETX as explained in Equation (5), a value of -50 is just sufficient as it can be divided by a WETX of 32 without resulting in a fraction.

Life-OF optimizes for time to first death in a single-parent routing topology and there is no OF that optimizes for this KPI that we are interested in. Therefore, we choose to compare Life-OF against MRHOF because it is mostly used in

TABLE 3 RPL configuration used for MRHOF and Life-OF

	MRHOF	Life-OF
HYSTERISIS	512	0.01
DAGMAXRANKINCREASE	768	0.05
MINHOPRANKINCREASE	256	1
MIN_RANK	256	-10^5
MAX_RANK	65535	-50

practice with RPL, in real deployments. This way, we can verify that the network time to first death is indeed improved using Life-OF.

To compare both OFs, we run four simulation scenarios: we configure RPL with each OF in a single-PHY network and in a multi-PHY network. We choose FSK 868 MHz for single-PHY networks since we are interested in coverage for long range settings. Since FSK 868 MHz has the longest range among the three PHYs, it is guaranteed to provide the same coverage range as a multi-PHY network. This allows to have a fair comparison between both OFs since the resulting networks will cover the same territory. Each scenario is run 50 times with random topologies generated in each run. We use a topology configuration with the area size of $2 \times 2 \text{ km}^2$, mimicking a typical industrial plant. We use a network size of 100 nodes which is an average size of an industrial network according to the IETF-defined use-cases.³³

At the end of each run, two KPIs are captured: network lifetime and network ETX. Network lifetime is calculated based on the simulated duration until the first node depleted all its battery energy. This KPI is essential to estimate a real cost of operating the network in many industrial use-cases. Network ETX is the distribution of the end-to-end ETX in the network. It is calculated for each node by summing the ETX of each link on the path from that node to the root. This KPI reflects the end-to-end latency which is necessary to observe how each OF impacts the upper bounds of latency in the network.

To report the results across multiple runs for each KPI, we plot a statistical description of the distribution of measurements using box plots. Box boundaries represent the first and third quartiles of the distribution. A red horizontal line represents the median. Individual outliers are plotted as individual data point.

6 | RESULTS

This section presents the results of the simulation runs. We organize this section in four parts: First, we present a network topology example and we show the performance of Life-OF in comparison with MRHOF, on this multi-PHY network. Second, we evaluate the performance of both OFs in bulk simulations in a single-PHY context. Third, we also evaluate the performance of both OFs in bulk simulations, but in a multi-PHY context. Fourth, we present the combined results in aggregate plots, side-by-side, for a global view of the results from all simulations.

6.1 | Example topology

This section presents an example topology to illustrate how Life-OF improves network lifetime in comparison to MRHOF by harnessing the benefits of diverse PHYs. Figure 4 shows the resulting topology when using MRHOF in a multi-PHY network. As seen in the figure, using MRHOF results in a network that is purely based on FSK 868 MHz. As MRHOF exclusively optimizes for ETX, it ends up selecting FSK 868 MHz throughout the network, irrespective of its energy hungry footprint. This causes the network to ignore higher bitrate links with ETX lower than FSK 868 MHz, despite their energy efficiency. It also causes the network to maintain the same routing topology over time without adapting to avoid paths close to the end of their lifetime.

Applying Life-OF to the same topology as Figure 4 results in a different routing topology, which is plotted in Figure 5. As observed in the plot, Life-OF results in a routing topology that combines the low bitrate FSK 868 MHz radio with high bitrate OFDM 868 MHz radio. It uses FSK 868 MHz links to communicate directly with the gateway, thus saving energy of routers. It uses multi-hop OFDM 868 MHz links, where it makes sense, in order to save energy of leaf nodes.

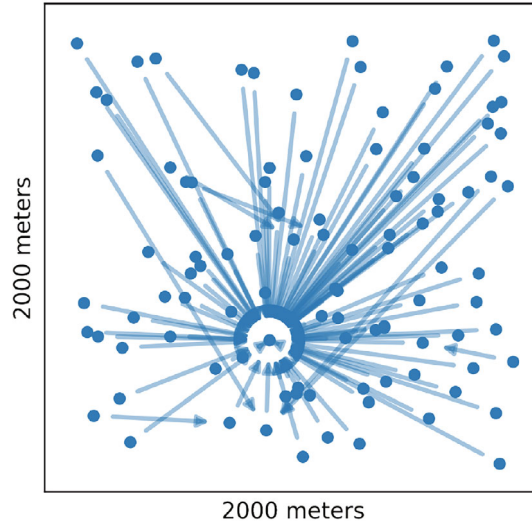


FIGURE 4 Example of a resulting routing topology when using MRHOF. The latter selects FSK 868 MHz links throughout, as a result of optimizing for ETX only

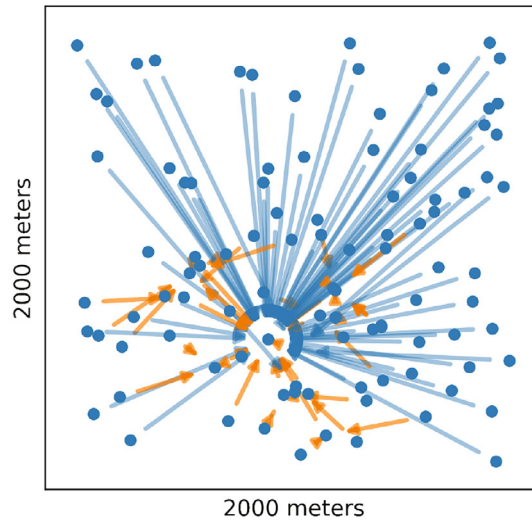


FIGURE 5 Example of a resulting topology using Life-OF that makes use of diverse PHYs to improve network lifetime

We note that as the network is aging, Life-OF re-calculates its routing topology by detecting nodes that are closest to death and establishing new routes with improved lifetime. This is contrary to MRHOF, which converges to a given topology that will remain the same for the entire simulated period, since the optimization is considering ETX only, without consideration to dying nodes. This is illustrated in Figure 6, which shows the evolution of estimated network lifetime for both OFs within the simulated durations. We observe that MRHOF starts with an already low network lifetime that keeps decreasing linearly until death at 0.8 years. By contrast, Life-OF is able to find a new network topology in each epoch that avoids nodes close to death, thus “pumping” life into the network in each epoch. This results into a network lifetime of 3 years which is 275% more than the lifetime achieved with MRHOF.

6.2 | Single PHY networks

This section presents the results of simulating a single-PHY network with Life-OF routing, in comparison to MRHOF. We observe in Figure 7 that using Life-OF yields nearly 400% the network lifetime of MRHOF. Even though this is a single-PHY network, using Life-OF still leads to adapting the routing topology at each epoch by selecting paths with higher lifetime. This way, the network is able to achieve an improved lifetime, even with the highest power consuming PHY. This demonstrates the benefit of using Life-OF even when the network is physically equipped with one PHY only.

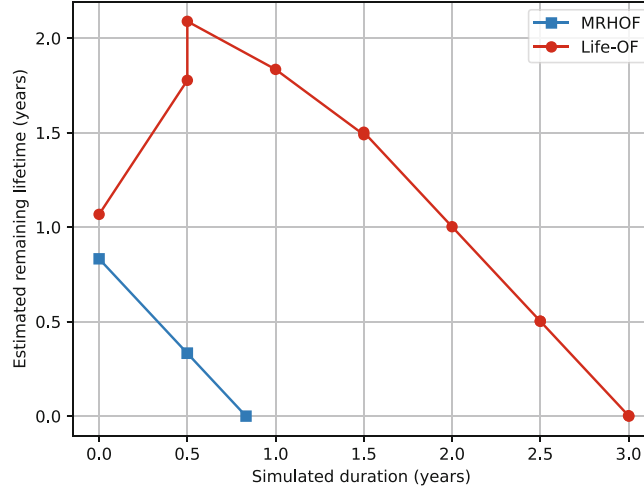


FIGURE 6 In the network demonstrated in 5, Life-OF adapts the network at each epoch by finding a topology that improves the network lifetime. This results in a lifetime 275% more than MRHOF

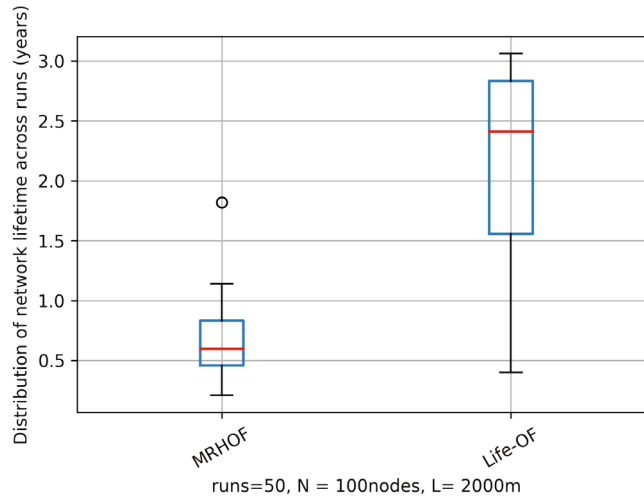


FIGURE 7 Life-OF yields 400% the network lifetime of MRHOF in single-PHY FSK 868 MHz setting

We show in Figure 8 the distribution of the resulting end-to-end ETX in the network. We observe that most of the ETX of the network using Life-OF is still at 1, same as MRHOF. Interestingly, MRHOF leads to more exceptions with higher end-to-end ETX than Life-OF, even though MRHOF optimizes for ETX alone. This happens because the hysteresis of MRHOF can cause it to ignore paths with small rank improvements (compared to the hysteresis of Life-OF, see Table 3).

6.3 | Multi-PHY networks

This section presents the results of simulating a multi-PHY network with Life-OF routing, in comparison to MRHOF. This is to demonstrate how both OFs perform when there are diverse PHYs available for routing. The distribution of network lifetime for both OFs is presented in Figure 9. We observe that using Life-OF results in improving the lifetime of the network by to be 470% of the lifetime of MRHOF. This is consistent with the pattern observed in Figure 6 that demonstrates the performance of routing with Life-OF, which keeps adapting the topology at each epoch to improve lifetime.

We show in Figure 10 the distribution of the resulting end-to-end ETX in the network. We observe that most of the ETX of the network using Life-OF is still at 1, same as MRHOF. As previously observed in the single-PHY networks, the rare cases where Life-OF leads to higher end-to-end ETX are more numerous. This is an expected side-effect of the use of multihopping with faster radios as illustrated in the topology in Figure 5. This way, Life-OF is able to save energy of the nodes in the network that are closest to the end of their lifetime.

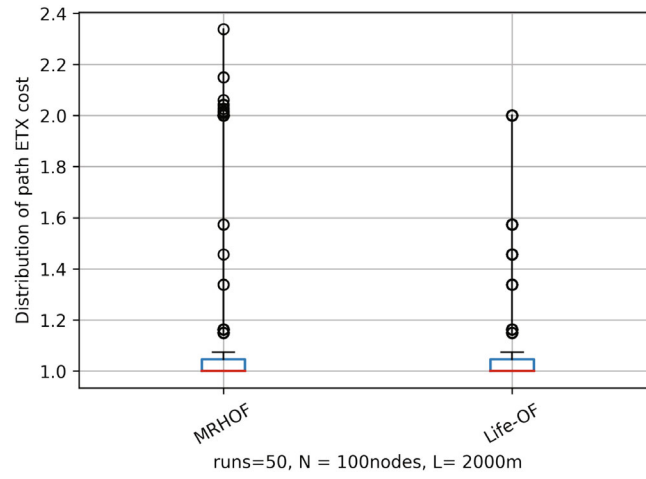


FIGURE 8 Most ETX of the network is still at 1, similar to MRHOF in single-phy network

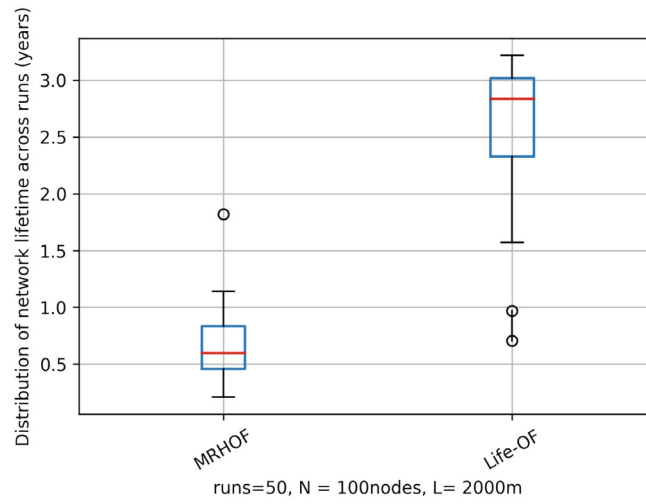


FIGURE 9 Life-OF yields 470% the network lifetime of MRHOF in multi-PHY setting

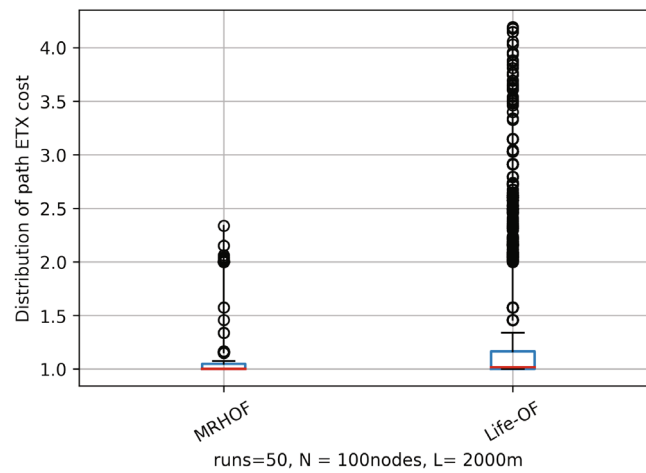


FIGURE 10 Most ETX of the network is still at 1, similar to MRHOF in the hybrid network

6.4 | Combined results

This section presents the aggregate simulation results for all scenarios in combined plots for a global comparison. The distribution of network lifetime for the four scenarios is plotted in Figure 11. Using Life-OF in combination with heterogeneous PHYs results in the highest network lifetime, with a median of nearly 2.8 years. Multi-PHY Life-OF results in a routing topology that makes use of high bitrate OFDM 868 MHz radio to save energy when possible by relaying through neighbors. It uses FSK 868 MHz links to communicate directly with the gateway, thus saving energy of routers. This way, it results in lifetime even higher than single-PHY Life-OF.

It is followed by using MRHOF in a single-PHY and multi-PHY networks where it shows the lowest network lifetime performance.

We observe that the ETX of most of the networks are still at 1 as shown in Figure 12. As previously observed, Life-OF shows more exceptional topologies with higher ETX than MRHOF.

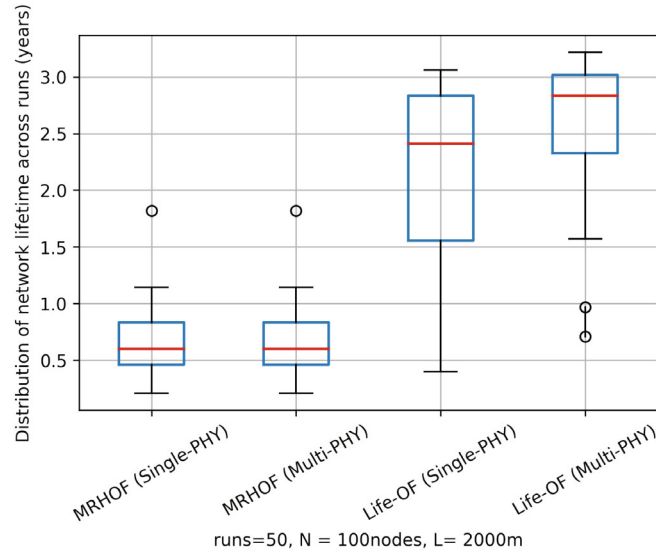


FIGURE 11 Best lifetime performance is achieved by using the hybrid network with Life-OF

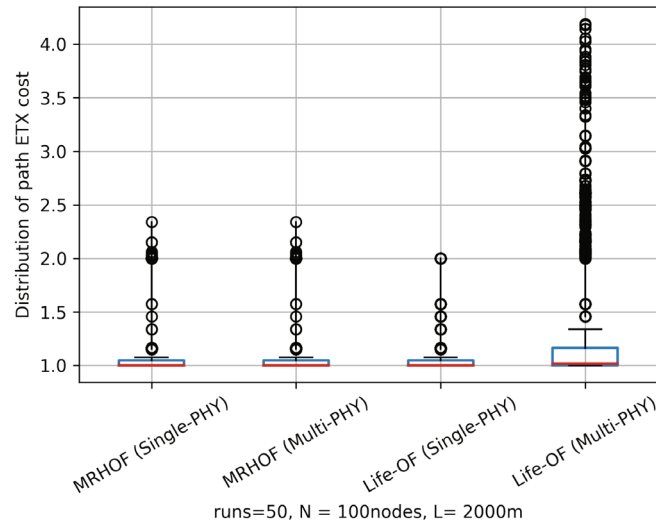


FIGURE 12 Most ETX of Life-OF using the hybrid network is still at 1, similar to other energy expensive settings

7 | CONCLUSION

In this article, we propose Life-OF, an OF that uses a combination of metrics in order to improve network lifetime using diverse PHYs. We demonstrated how the routing layer can consider the link quality, node's remaining lifetime, hop-count, and the characteristics of each available PHY to make routing decisions that improve the network's lifetime. We demonstrate how Life-OF can be defined using RPL protocol specifications. While our previous research on multi-PHY integration was based on firmware implementation in a fixed setup, this article explores multi-PHY routing in pseudo-randomly generated settings in simulation. This allows an exhaustive evaluation of the proposed multi-PHY OF that is not possible in a testbed setup.

We demonstrate the performance of Life-OF compared to classical MRHOF using simulations in single-PHY and multi-PHY settings. The simulations consider a scenario in a $2 \times 2 \text{ km}^2$ area. Simulation results demonstrate that MRHOF converges to a pure long-range FSK 868 MHz network, leading to lowest network lifetime. However, Life-OF is able to improve network lifetime by continuously adapting the routing topology to favor routing over nodes with relatively high remaining lifetime. It combines diverse PHYs in a way that balances power consumption in the network. This way, nodes can switch between using short range PHYs to improve their own battery lifetime or using long range PHYs to avoid routers that are close to depletion. Results show that using Life-OF yields 400% the network lifetime of MRHOF in a single-PHY setting. Furthermore, using Life-OF yields network lifetime at 470% that of MRHOF in a multi-PHY setting.

Future work will explore how Life-OF can be adapted to consider the overhead of control traffic for parent switching. This way, the node can avoid parent switching if there is not enough energy incentive. Furthermore, the model presented in this article can be generalized according to Reference 10 such that it optimizes for the operational costs of the network. This way, it favors routing over nodes that are less expensive to maintain as suggested by the IETF RFC on routing metrics.¹²

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