SD-LLN: A Novel Architecture Using SDN and NFV to Adapt RPL in Dynamic Low-Power and Lossy Network (LLN)

Manare Zerifi*, Abdellatif Ezzouhairi, and Abdelhak Boulaalam
Engineering, Systems and Applications Lab, ENSA, Sidi Mohamed Ben Abdellah University of Fez, Fez, Morocco
Email: manare.zerifi@usmba.ac.ma (M.Z.), abdellatif.ezzouhairi@usmba.ac.ma (A.E.), abdelhak.boulaalam@usmba.ac.ma (A.B.)

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*Corresponding author

***Abstract*—In Low-Power and Lossy Networks (LLNs), significant challenges arise due to the severe constraints on energy, memory, and processing capacities. These limitations hinder the efficiency of routing protocols like Routing Protocol for Low-Power and Lossy Networks (RPL), particularly in dynamic network topologies where frequent changes occur. We propose an innovative architecture integrating Software Defined Networking (SDN) and Network Function Virtualization (NFV) with RPL protocol to address this issue. SDN and NFV technologies introduce greater flexibility, programmability, and centralized control, enabling the network to adapt more effectively to dynamic changes. Our proposed Software Defined architecture for Low-Power and Lossy Network (SD-LLN) leverages these technologies to enhance RPL's adaptability and resilience in varying network conditions. We improve network performance by integrating SDN/NFV with RPL, particularly in routing efficiency, stability, and resource optimization. Compared to traditional RPL implementations, our approach demonstrates significant advantages in providing an efficient and dynamic solution for managing dynamic LLNs. The results highlight the potential of this method in managing LLNs, offering a robust framework to effectively overcome dynamic, resource-constrained environments.**

***Index Terms*—Low-Power and Lossy Networks (LLNs), Internet of Things (IoT), Network Function Virtualization (NFV), Routing Protocol for Low-Power and Lossy Networks (RPL), Software Defined Networking (SDN)**

I. Introduction

The Internet of Things (IoT) has received attention and has known a rapid evolution [1, 2]. Within this expansive network, lossy and low-power networks constitute a distinct category that suffers from constrained storage and energy resources [3, 4]. However, they are utilized in diverse applications, like industrial settings and smart cities. Nevertheless, managing the low-power and lossy networks within dynamic environments presents essential challenges concerning node mobility and topology changes [5, 6].

The Routing Protocol for Low-Power and Lossy Networks (RPL) protocol emerges as a prominent choice for limited networks owing to its lightweight nature and adeptness in adapting to such constraints [7]. Nonetheless, this protocol encounters several limitations in dynamic network conditions and the imperative of ensuring reliable communication [8, 9].

This study proposes an architecture that integrates the foundational principles of software-defined networking and network function virtualization with RPL, aiming to address the complexities inherent in dynamic Low-Power and Lossy Network (LLN) environments [10, 11]. By exploiting the flexibility and programmability of software defined networking and network function virtualization.

Our methodology follows a structured progression. We start with a comprehensive literature review explaining the nuances of RPL, Software Defined Networking (SDN), and Network Function Virtualization (NFV). Subsequently, we analyze existing studies in this domain, concluding with a detailed description of our proposed architecture and its constituents. We then present an analysis of our approach's effectiveness to ascertain our architecture's strengths and weaknesses, demonstrating its potential for LLN management. In conclusion, our study proposes a new architecture aimed at enhancing the capabilities of LLNs through the integration of SDN/NFV with RPL, especially in dynamic conditions.

II. Background

A. Routing Protocol for Low Power and Lossy Networks

The RPL was produced by the Internet Engineering Task Force (IETF) to meet routing needs. It is a highly efficient solution to manage networks with constrained performance capabilities. Operating on a multi-hop concept, RPL navigates from source to destination nodes through intermediary nodes organized within a directed acyclic graph [12, 13]. This graph structure forms a tree topology, offering both flexibility and efficiency to the routing process. RPL achieves this by dynamically selecting the most optimal path using an objective function, ensuring lightweight and adaptive routing functionality [14, 15].

RPL incorporates two essential objective functions:

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OF0 (zero objective function), which assigns a value to the previous rank, and MRHOF (minimum rank with hysteresis objective function), which optimizes routing by minimizing a specific metric and selecting the most efficient paths.

In a simple topology of an RPL architecture, source nodes at the base of the hierarchy gather data from their environments and transmit it upwards through the network. These source nodes, limited by constrained energy and processing resources, depend on relay nodes to forward the collected data efficiently. Relay nodes act as intermediaries, ensuring the data reaches the sink node, which is positioned at the top of the hierarchy and has considerably greater processing capabilities. This hierarchical structure enables scalable and energy-efficient communication within resource-constrained networks.

Although this protocol is suitable for low-power networks, it has several constraints that restrict its usefulness. These limitations are especially apparent in dynamic contexts where network conditions are subject to rapid changes. The dynamic character of these environments poses difficulties in adjusting to changing topologies. It was unable to maintain reliable communication with rapid network changes, which could cause interruptions in connectivity and data transmission. Furthermore, the protocol needs more improvements to adapt to dynamic network changes [16].

B. Software Defined Networking

SDN has emerged as a transformative concept, redefining how modern networks are managed and operated. At its core, SDN centralizes the intelligence that was once distributed across individual network devices into a single, unified component known as the SDN controller. Acting as the brain of the network, the controller takes on the responsibility of making decisions about how data flows, routing and policies are handled. This centralization not only simplifies management but also enables dynamic programming, allowing networks to swiftly adapt to new demands, technologies, or applications.

The importance of this approach lies in its division of responsibilities: network devices, which traditionally carried both decision-making and execution burdens, are now streamlined to perform one task, executing the instructions provided by the SDN controller. This shift is a revolutionary leap in networking paradigms, introducing unprecedented levels of agility, efficiency, and scalability. By separating control from physical infrastructure, SDN empowers organizations to build networks that are more responsive to their unique needs, enhancing innovative applications and more efficient resource utilization [17, 18].

C. Network Function Virtualization

NFV is transforming the way networks are built and managed. Instead of depending on large, costly hardware dedicated to specific tasks like firewalls, routers, or load balancers, NFV moves these functions into software. This software runs on general purpose hardware, allowing a single physical device to perform multiple virtualized tasks, making the network more efficient and flexible.

What makes NFV so powerful is its ability to adapt to changing needs. Network services can be set up or adjusted on demand, whether it's to handle a sudden spike in traffic, support new applications, or optimize resources in real time. This flexibility not only speeds things up but also ensures you're only using what you need, exactly when you need it.

On top of that, NFV is cost effective. By reducing the dependence on specialized hardware, it lowers upfront costs, cuts down on maintenance, and even helps save energy. It is also a huge boost for innovation and deploying new network features becomes faster and easier.

These challenges, which hinder RPL's performance in dynamic environments, can be addressed by incorporating two promising technologies: SDN and NFV [19]. By integrating these solutions, the network becomes more flexible and programmable, seamlessly adapting to node mobility and evolving network topologies [20, 21].

Leveraging the strengths of SDN and NFV, the network can better navigate dynamic conditions, improving its resilience and overall efficiency [22, 23].

III. Related Works

This section reviews the significant existing works presented on the integration of SDN and NFV with RPL.

This work [24] introduced a hybrid software-defined RPL approach, which incorporates three distinct objective functions tailored to address specific network needs. The innovative aspect of this approach lies in its ability to dynamically select the optimal objective function using the Killer Whale Optimization (KWO) algorithm, ensuring efficient energy consumption and improved network performance. The proposed model demonstrates significant improvements, including reduced control message overhead, enhanced Packet Delivery Ratio (PDR), and better energy efficiency compared to existing solutions like a versatile out of-band and a cross-layer control of data flows. However, some limitations remain. The use of the KWO algorithm, while effective, may introduce computational overhead, which could strain resource-constrained IoT devices. Additionally, the paper primarily addresses scenarios with stable or minimally dynamic node mobility.

This work [25] presented a Reliable Mobility Management of RPL (RM-RPL) designed to enhance RPL's performance in dynamic environments. The framework introduces a novel objective function that optimizes parent selection, improving route stability by enabling mobile nodes to function as both routers and parents simultaneously, without creating network loops. This innovative approach addresses key challenges in dynamic IoT scenarios. Simulations demonstrate that RM-RPL achieves significant improvements in PDR and power efficiency compared to existing protocols such as the reverse trickle timer-based RPL, Dynamic RPL, and the energy and mobility aware routing for the internet of mobile things. However, the reliance on additional control packets introduces overhead, which may not align well with the constraints of low-power and lossy networks. Moreover, while the framework accounts for mobility, it assumes that some nodes remain static, limiting its applicability in fully dynamic networks.

This paper [26] introduced an enhanced Objective Function (OF) for the RPL in IoT systems, designed to address critical limitations of traditional RPL. By integrating multiple metrics into the parent selection process, the proposed approach improves route stability and mitigates issues such as frequent parent switching and accelerated energy depletion of nodes. These enhancements aim to extend network lifetime and improve overall performance, tackling some of the fundamental challenges that limit the effectiveness of standard RPL. However, while the proposed solution demonstrates potential, it has notable limitations. The study assumes a static network for all scenarios, overlooking the role of mobility as a crucial factor in real-world IoT environments where devices often move dynamically. Furthermore, the paper does not include a detailed analysis of the overhead introduced by the enhanced OF.

A key innovation of [27] is the scheduling algorithm, which is designed to minimize reconfiguration overhead and reduce energy consumption. By targeting only the necessary updates in the network, the algorithm improves overall efficiency and reduces the impact of topology changes. Simulation results demonstrate notable improvements in metrics such as PDR, control overhead, and energy efficiency. However, the study has certain limitations. It does not account for dynamic traffic patterns, which are a common feature in real-world industrial IoT scenarios.

A resource-aware SDN/NFV-based low-power IoT system, which was called SoftIoT in [28], presented an innovative framework that integrates SDN and NFV to enhance the performance of IoT networks. This approach prioritizes key objectives such as energy optimization and interference reduction, addressing some of the most pressing challenges in IoT environments. By streamlining network tasks and optimizing resource allocation, this method minimizes operational overhead, improves energy efficiency, and significantly reduces interference between devices. These advancements contribute to creating a more scalable, efficient, and reliable IoT ecosystem, especially in scenarios with high device density and diverse application requirements. Despite its promising contributions, the study has certain limitations. The interference prediction and energy optimization models employed are relatively simplistic, which may limit the system's effectiveness in complex or highly dynamic environments.

Sanmartin *et al*. [29] introduced a novel architecture of SDN using the RPL protocol for internet of things, named SBR, which leverages the integration of software defined networking with the routing protocol for low-power and lossy networks to address critical challenges in the IoT environments. By combining the centralized intelligence of SDN with the adaptability of RPL, the SBR architecture provides a robust framework for enhancing routing efficiency in dynamic and resource-constrained IoT networks. The SBR architecture is further augmented by implementing the SIGMA objective function, specifically designed to optimize routing decisions. The SIGMA objective function plays a pivotal role in dynamically adjusting routing paths based on real-time network conditions, ensuring a more efficient distribution of data flows and minimizing congestion in highly active IoT deployments. This adaptability is crucial in IoT scenarios where network topology is frequently changing due to node mobility, energy constraints, or environmental interferences.

Rabet *et al*. [30] presented a significant advancement in enhancing the RPL protocol within dynamic IoT environments by introducing an SDN-based mobility management architecture, named SDMob. This architecture leverages the principles of SDN to shift the control functions traditionally handled by individual nodes to a centralized controller. By offloading these tasks, SDMob reduces the computational burden on resource-constrained IoT devices and enables the implementation of more sophisticated algorithms, such as the particle filter and unscented Kalman filter (UKF). The ability to accurately determine the position of nodes in a dynamic network environment directly influences the stability of routing paths and the overall efficiency of data transmission. Given that traditional RPL struggles with mobility due to its reliance on static topologies and predefined routes, the integration of SDMob provides a much-needed solution to the inherent limitations of conventional approaches.

The works referenced in [24–30] explore different strategies of enhancing routing and network management. These studies, while innovative in their use of SDN, NFV, they address static or minimally dynamic environments. For example, in [24] and RM-RPL [25], they do not fully address the challenges posed by dynamic LLN environments with frequent topology changes. While SoftIoT [28] and the SDMob architecture [30] aim to enhance energy efficiency and mobility, they are not suitable to high levels of dynamism.

In contrast, our approach utilizes two types of controllers, a local and a global SDN controller. The local controller oversees local network conditions like node mobility or link failure, but the global SDN controller focuses on the global decisions due to its global view of the entire network. This model aims to share the control between two types of controllers to ensure energy and overhead optimization, which is very crucial for LLN networks and constrained devices, see Table I.

Table I clearly compares different papers and their contributions, emphasizing the gaps, strengths, and contributions that our work addresses. This contribution highlights our work's advancement and explains current approaches' strengths and weaknesses.

TABLE I: COMPARISON OF EXISTING WORKS

Paper	Approach	Contribution	Weakness	Gap addressed by our work
[24]	Integration of SDN with three dynamic objective functions (TriOF).	Introduces dynamic OF selection (energy efficiency, mobility, and link stability) using the Killer Whale Optimization (KWO) algorithm.	KWO introduces computational overhead; assumes stable network with limited dynamic mobility.	Shares control dynamically between local and global controllers, addressing computational overhead and dynamic network challenges.
[25]	Reliable Mobility Management framework for RPL.	Introduces mobility support by optimizing parent selection and improves PDR and energy efficiency.	Assumes partial static topology; relies on additional control packets, increasing overhead.	Supports fully dynamic IoT networks with efficient local-global control sharing to minimize overhead and enhance scalability.
[26]	Multi-metric objective function for RPL.	Improves parent selection using ETX, residual energy, and load metric, addressing traffic load imbalance, routing instability, and energy inefficiency.	Assumes static networks; lacks mobility considerations and overhead analysis.	Combines SDN and NFV to address mobility and scalability, with adaptive mechanisms to minimize overhead and improve routing.
[27]	SDN-based centralized control for scheduled networks.	Improves reliability and energy efficiency with reconfiguration mechanisms and scheduling algorithms.	Limited scalability due to centralized control; lacks NFV integration.	Introduces distributed control sharing to enhance scalability and integrates NFV for better resource utilization.
[28]	Proposes the SoftIoT framework, which integrates SDN and NFV to enhance IoT networks, with a particular focus on optimizing energy consumption and improving overall network efficiency.	Implements service chaining in SDN and NFV to enhance energy efficiency.	-Uses a simple model, simplistic for interference and energy.	Energy optimization in the context of dynamic networks.
[29]	Introduces a streamlined SBR architecture that integrates software-defined networking and network function virtualization with the Routing Protocol for Low-Power and Lossy Networks (RPL), aiming to optimize the performance, scalability, and resource efficiency of IoT networks.	Proposes a scalable and dynamic architecture leveraging SDN.	Limited scalability and performance in dynamic, mobile environments.	Addresses dynamic network conditions.
[30]	An SDN-based architecture that incorporates Particle Filter and Unscented Kalman Filter (UKF) algorithms to enhance system accuracy, robustness, and adaptability in dynamic network environments.	Improved mobility management, PDR, and energy efficiency through centralized control and advanced filtering.	Increased complexity and potential control traffic in larger networks.	Provides a solution for mobility management in dynamic IoT networks by optimizing energy consumption and reducing control overhead through SDN and NFV.

IV. PROPOSED ARCHITECTURE

A. Problem Definition

In constrained IoT environments, known as low-power and lossy networks, devices face significant limitations, such as low battery life, limited processing power, and minimal memory. To meet these constraints, RPL was developed as a lightweight routing protocol tailored for LLNs. While RPL works well in stable or semi-static networks, it struggles in dynamic environments where the network topology, traffic patterns, device locations, and other factors change frequently. This lack of adaptability arises because RPL does not have a global view of the network, leading to problems like increased packet loss, unstable routes, and higher energy consumption.

To address these issues, integrating software-defined networking and network function virtualization has been proposed. SDN provides a centralized view of the network, allowing better decision-making, while NFV offers flexible resource management. However, this solution comes with its challenges: the large number of control messages exchanged between the SDN controller and network nodes can significantly increase overhead and drain energy, which is especially problematic in resource-constrained LLNs.

To solve this, our approach combines SDN and NFV with a localized control mechanism. Instead of relying entirely on the SDN controller, we propose delegating local decision-making to the sink node. The sink manages immediate, localized decisions for nearby nodes, while periodically sending updates to the SDN controller, which has a global view of the entire network. This hybrid approach reduces the number of control messages, minimizes overhead, and conserves energy, while still benefiting from the global insights of SDN. By enhancing RPL with this dual-layer control strategy, we make it more adaptable to dynamic IoT environments, ensuring better energy efficiency, lower latency, and more stable routing.

B. System Model

In this section, we introduce Software Defined

Architecture for Low-Power and Lossy Network (SD-LLN), an advanced architecture designed to optimize RPL performance in IoT networks with dynamic topologies and constrained resources. By leveraging SDN and NFV, SD-LLN minimizes overhead and energy consumption while significantly enhancing the PDR.

The architecture is built around resource-constrained IoT nodes (N_1, N_2, ⋯, N_n) operating in low-power and lossy networks environments where energy, memory, and processing power are inherently limited. These nodes sense and transmit data to a sink node, which acts as a local controller, managing real-time decisions for parent selection and routing. In our context, real-time decision refers to local actions taken within 100 ms to 200 ms to ensure timely route adjustments in response to changing link or node conditions. The sink node is responsible for handling immediate networking tasks at the local level and adjusting routes dynamically in response to local conditions. While the sink node does perform some local decision-making, it has partial global visibility, which it uses to periodically compile and transmit network summaries to the SDN controller.

At a higher level, the SDN controller plays the role of a global network manager, maintaining a holistic view of the network. It collects updates from the sink node, optimizes routing, and dynamically allocates resources to adapt to changing network conditions. While the sink node handles immediate local control, the SDN controller oversees the entire network's performance, ensuring strategic, network-wide optimizations. NFV further enhances flexibility by dynamically assigning resources based on traffic patterns, ensuring smooth operation even in fluctuating network environments.

The system organizes itself into a destination-oriented directed acyclic graph using an enhanced OF tailored for RPL. This function considers multiple factors, such as energy levels, node mobility, and link stability, to determine the optimal parent selection, ensuring efficient data forwarding.

To maintain optimal performance, the sink node continuously monitors local conditions, dynamically adjusting routes and handling real-time reconfigurations. Periodically, it compiles and transmits network summaries to the SDN controller, which then analyzes the overall network state, updates routing tables, and fine-tunes resource distribution.

By combining localized real-time control at the sink node with global optimization managed by the SDN controller, SD-LLN achieves a well-balanced hybrid control mechanism. This synergy allows the system to adapt seamlessly to dynamic network topologies, making real-time adjustments at the local level while ensuring strategic, network-wide optimizations. As a result, SD-LLN effectively reduces energy consumption, enhances network efficiency, and maintains consistent, high-performance data transmission, even in challenging and ever-changing IoT environments, see Fig. 1.

Fig. 1 presents the essential components of our proposed SD-LLN architecture, highlighting the concept of a dual controller that shares control between two types of controllers: local and global.

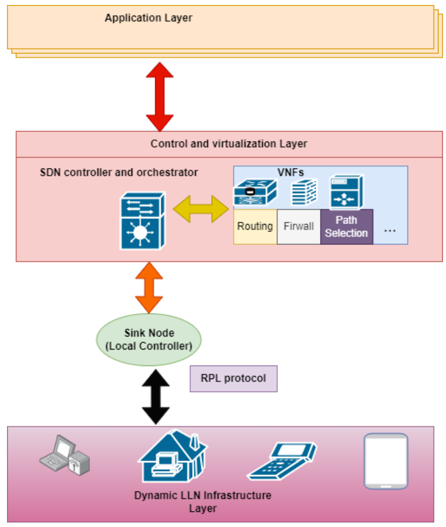

Fig. 1. Proposed SD-LLN architecture for LLN network.

V. Simulation Results and Analysis

In this section, we assess the performance of the proposed model through comprehensive simulations and compare its results against those of existing approaches.

A. Simulation Environment

TABLE II: SIMULATION PARAMETERS

Parameter	Value
Simulation Area	1000 × 1000 m
Number of IoT Nodes	100
Number of Gateways	3
Number of OpenFlow Switches	15
Number of Controllers	1 (SDN Global Controller)
Sink Node (Local Controller)	1
Initial Energy of IoT Nodes	20 Joules (Maximum)
Flow Table Size	1000 KB
Packet Size	512 KB (Maximum)
Data Rate	1.1 Mbps
Simulation Time	100 minutes
Modules	IoT_Module, Sink_Module (Local Control), Flow_Monitor_Module, OpenFlow_Module

The proposed SD-LLN architecture was evaluated using a comprehensive simulation environment that models the interaction between LLN nodes, the sink node, and the SDN controller. The simulation utilized Cooja to simulate dynamic LLN nodes and their interaction with the sink node, while Mininet was employed to simulate the SDN controller and NFV operations. In our context, our enhanced OF incorporates important parameters to optimize energy consumption, minimize overhead, and enhance PDR. These parameters include Energy Levels to conserve energy, Node Mobility to ensure stable connectivity, Link Stability to prioritize reliable links in fluctuating conditions, and Traffic Load Distribution to balance congestion and optimize network resources. This setup facilitated seamless collaboration between the sink node in Cooja, acting as a local controller, and the SDN controller in Mininet, serving as a global controller. The algorithms for the architecture were implemented using Contiki OS for the LLN nodes and Python for the SDN control logic. The simulation parameters are detailed in Table II.

This table provides the key parameters to model the SD-LLN architecture. It presents the physical and technical aspects of the simulation environment, and these parameters are very important to evaluate the performance of our architecture.

B. Comparative Analysis

After the simulation, the results were analysed for a comprehensive comparative assessment. We focused on key performance metrics, including control overhead, energy consumption, and PDR. The obtained results were compared against the SoftIoT framework.

1) Comparison of control overhead

Control overhead refers to the proportion of control packets compared to the network's total number of transmitted packets. In our model, we reduced control overhead to 0.60 when using 100 IoT nodes. In contrast, SoftIoT recorded a higher overhead of 0.83 for the same number of nodes. These results clearly show that our approach helps minimize unnecessary control traffic, leading to more efficient energy usage in the network.without any data protection see Fig. 2.

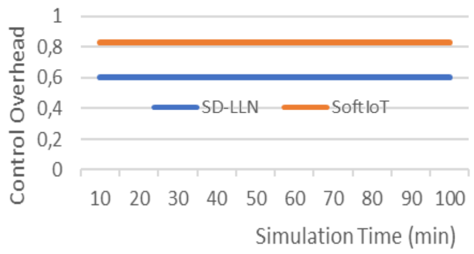

Fig. 2. Comparison of control overhead.

2) Comparison of packet delivery ratio

In our proposed architecture, the PDR increases gradually over time, reaching nearly 95% after 90 minutes of simulation. In contrast, SoftIoT also shows an increasing PDR over time but remains below that of SD-LLN, hovering around 90%, see Fig. 3.

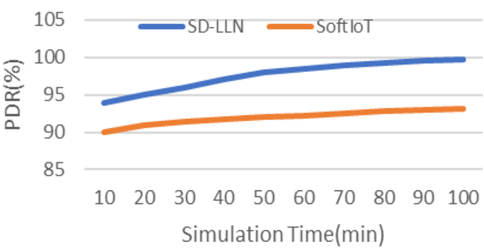

Fig. 3. Comparison of packet delivery ratio.

3) Comparison of energy consumption

Energy consumption refers to the total amount of energy used by the network throughout its operation. As shown in the figure, our proposed SD-LLN architecture demonstrates superior energy efficiency compared to other models. At the 10-minute mark, the average energy consumption of our model is 6.5 J, gradually increasing to 16 J by the end of the simulation (100 minutes). In contrast, SoftIoT consumes 8 J at the same point. These results highlight the efficiency of our approach, which optimizes resource utilization and minimizes unnecessary transmissions by leveraging the local controller, see Fig. 4.

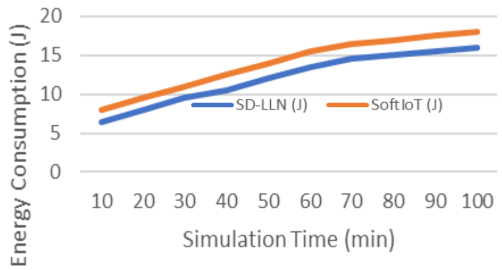

Fig. 4. Comparison of energy consumption.

TABLE III: COMPARISON OF KEY METRICS

Key metrics	Our approach (SD-LLN)	SoftIoT
Control overhead	0.60	0.83
Packet Delivery Ratio	95%	90%
Energy consumption	6.5J	8J
Latency	120ms	210ms

Table III provides a comparison of key metrics between SD-LLN and SoftIoT.

VI. DISCUSSION

Our results show that the proposed model improves several essential metrics such as energy efficiency, overhead and packet delivery ratio. By integrating software-defined networking and network functions virtualization our approach enhances the IoT architecture, making it particularly effective in dynamic environments where resource limitations pose special challenges. The flexibility introduced by this integration allows for better resource management for maintaining an efficient network.

The idea of our approach is the combination of both local and global controllers. This hybrid control mechanism plays a critical role in reducing system overhead, which is crucial in optimizing overall network performance. The local controller deals with specific local duties, and the global controller manages the entire network.

The reduced overhead is critical to maintaining high efficiency with IoT-constrained networks. That is validated by the improvement in the packet delivery ratio. The improved PDR demonstrates the potential of our approach to ensure stable communication in limited environments and enable reliable data transmission.

The combination of SDN, NFV, and dual control mechanisms offers an important solution for low-power and lossy networks. The proposed architecture is suitable for addressing the challenges posed by constrained environments, and our results suggest that it can provide significant improvements in terms of energy efficiency, performance, and reliability. This proposed solution can have significant implications for real-world IoT applications like Smart Cities or Industrial IoT.

VII. Conclusion

In this paper, we present an SDN/NFV-based model for RPL in dynamic environments, aiming to maintain network performance under changing conditions while addressing the constraints of low-power and lossy network devices. Our approach leverages SDN and NFV to manage device mobility. However, the frequent exchange of messages between the SDN controller and devices can lead to increased overhead, negatively impacting PDR and energy efficiency.

To address this challenge, our model introduces a distributed control mechanism by dividing control functionality between two types of controllers. The sink acts as a local controller, handling real-time local decisions and aggregating updates before transmitting them to the SDN controller, which, in turn, makes global decisions based on a holistic view of the network. This approach effectively reduces overhead while optimizing energy efficiency and PDR, as demonstrated by our results.

As future work, we envisage testing our proposed architecture on a large scale and in real-world environments. As second interesting aspect is integrating machine learning algorithms to ensure proactive and efficient management of resources.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Manare Zerifi contributed to the design of the architecture, simulations, and manuscript writing. Abdellatif Ezzouhairi contributed to the development of the SDN/NFV framework and performance analysis. Abdelhak Boulaalam guided the theoretical framework and contributed to the manuscript revision. All authors had approved the final version.

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Manare Zerifi received her M.S. degree in internet of things and mobile systems from ENSA-Fez, the University of Sidi Mohamed Ben Abdellah Fez, Morocco, in 2019. She is currently a Ph.D. candidate at the University Sidi Mohamed Ben Abdellah Fez, Morocco. Her research interests include: IoT, SDN, NFV, fog computing.

Abdellatif Ezzouhairi received the Ph.D. and the M.Sc. degrees in mobile computing from Ecole Polytechnique, Montreal, Canada; the engineering degree in computer sciences from ENSIAS, Rabat, Morocco. He was an associated researcher at the Mobile Computing and Networking Research Laboratory, Chair Ericsson Canada. He is now a full professor at USBMA-ENSA University, Morocco. His research interests cover mobile network integration and the internet of things.

Abdelhak Boulaalam is a professor in Department of Electrical and Computer Engineering at, the National School of Applied Sciences, Sidi Mohamed Ben Abdellah University, and Fez, Morocco. He received a Ph.D. degree in computer science from Sidi Med Ben Abdellah University. He holds the M.Sc. (USMBA University, Morocco) degrees in computer sciences. He has published some journal and conference articles and book chapters in the areas of IoT, intelligent products, IMS, product data management, and PLM. He also serves as a reviewer for various journals and conferences.