IoT

MDPI

Article

Routing Protocols Performance on 6LoWPAN IoT Networks

Pei Siang Chia [1], Noor Hisham Kamis [1], Siti Fatimah Abdul Razak [1,*], Sumendra Yogarayan [1], Warusia Yassin [2] and Mohd Faizal Abdollah [2]

1 Faculty of Information Science and Technology, Multimedia University, Melaka 75450, Malaysia; noorhisham.kamis@mmu.edu.my (N.H.K.); sumendra@mmu.edu.my (S.Y.)
2 Faculty of Information and Communication Technology, Universiti Teknikal Melaka, Melaka 76100, Malaysia; s.m.warusia@utem.edu.my (W.Y.); faizalabdollah@utem.edu.my (M.F.A.)
* Correspondence: fatimah.razak@mmu.edu.my

Abstract: IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN) are specifically designed for applications that require lower data rates and reduced power consumption in wireless internet connectivity. In the context of 6LoWPAN, Internet of Things (IoT) devices with limited resources can now seamlessly connect to the network using IPv6. This study focuses on examining the performance and power consumption of routing protocols in the context of 6LoWPAN, drawing insights from prior research and utilizing simulation techniques. The simulation involves the application of routing protocols, namely Routing Protocol for Low-power and Lossy (RPL) Networks, Ad hoc On-demand Distance Vector (AODV), Lightweight On-demand Ad hoc Distance-vector Next Generation (LOADng), implemented through the Cooja simulator. The simulation also runs in different network topologies to gain an insight into the performance of the protocols in the specific topology including random, linear, and eclipse topology. The raw data gathered from the tools including Powertrace and Collect-View were then analyzed with Python code to transfer into useful information and visualize the graph. The results demonstrate that the power consumption, specifically CPU power, Listen Power, and Total Consumption Power, will increase with the incremental of motes. The result also shows that RPL is the most power-efficient protocol among the scenarios compared to LOADng and AODV. The result is helpful because it brings insights into the performance, specifically power consumption in the 6LoWPAN network. This result is valuable to further implement these protocols in the testbed as well as provide an idea of the algorithmic enhancements.

Keywords: AODV; Cooja; LOADng; RPL; 6LoWPAN

Academic Editor: Amiya Nayak

Received: 6 October 2024
Revised: 21 January 2025
Accepted: 23 January 2025
Published: 10 February 2025

Citation: Chia, P.S.; Kamis, N.H.; Abdul Razak, S.F.; Yogarayan, S.; Yassin, W.; Abdollah, M.F. Routing Protocols Performance on 6LoWPAN IoT Networks. *IoT* **2025**, *6*, 12. https://doi.org/10.3390/iot6010012

1. Introduction

According to a previous study, 24 billion IoT devices were available globally in the year 2020. This forecast suggested that, on average, there would be approximately four Internet of Things (IoT) devices for every individual [1]. IoT devices typically constitute low-power and lossy networks (LLNs), characterized by numerous motes that operate under strict constraints, especially on energy consumption. Due to the hardware limitations, the performance of an LLN is tied to the efficiency with which routing protocols are used. The radio transmission activity significantly influences the energy consumption of individual devices within a wireless sensor network (WSN).

The selection of appropriate routing protocols can directly impact the overall energy consumption level. In other words, the protocol selection and control packet management can optimize energy efficiency and enhance the performance of WSNs [2]. Data redundancy occurs when the WSN sensor nodes are densely clustered due to the effort to improve the probability of obtaining a suitable neighbor to transmit the data [3]. The rise in packet size transmitted across nodes and the concurrent goal of reducing power consumption within routing protocols poses significant challenges. Routing protocols for low-power networks must effectively manage packet delivery while minimizing energy consumption. As packet sizes increase, the complexity of managing these packets also grows, leading to greater processing demands on sensor nodes with limited computational capabilities. This increased complexity can adversely affect the performance of energy-efficient routing algorithms. This prompts a critical examination of routing protocols to determine whether they can effectively operate within the low constraints inherent in the IoT concept, particularly in the context of IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN).

Evaluating the effectiveness of other routing protocols in the context of 6LoWPAN presents challenges, in part because the routing protocol for low power and lossy networks (RPL) has received a lot of attention from the academic and research communities. The understanding of IoT vulnerabilities, like rank attacks and blackhole attacks is expanded from previous studies, mainly by RPL. Through the assessment of standardized protocols such as RPL, Ad hoc On-Demand Distance Vector (AODV), and Lightweight On-Demand Ad hoc Distance Vector Routing Protocol—Next Generation (LOADng), a benchmark between modified protocols from previous research can be established. Additionally, analyzing recognized protocols thoroughly can help identify potential shortcomings that will lead to future improvements. This iterative process is especially helpful in addressing common issues, like energy consumption, in a variety of scenarios, which will promote advancements and optimize routing protocols within the 6LoWPAN.

A variety of performance metrics have been reported for assessing routing protocol effectiveness in the context of 6LoWPAN. A certain amount of the academic literature emphasizes the use of Powertrace extension, especially when it comes to simulations with Cooja. This preference derives from the inherent characteristics of the Powertrace dataset, which contains essential parameters, most notably overall CPU power usage and energy dissipation in the low power mode (LPM). Specifically, this dataset represents an extensive collection of information relevant to the artificially created normal IoT network environment, outlining complex aspects of energy dynamics present in the motes [4]. Apart from that, Hayati et al. [5] presents exhaustive data on power utilization which was extracted from the Powertrace output. The output delineates power consumption metrics for individual motes, with a focus on incremental motes and transmission ranges of 50 and 100 m. Ching et al. [6] proposed that energy estimate is a critical factor in the LLN and a surrogate for the detector lifetime. They performed analyses to determine how different topologies, and the addition of more motes affect the dynamics of energy usage. They used the Powertrace tool to confirm their findings, which show that an increase in node count is correlated with an increase in energy usage. Khlaifi et al. [7] and Glissa and Meddeb [8] tried to assess the efficacy of different protocols. Consistently, research results showed that using Powertrace, the number of motes added incrementally across both protocols was accompanied by a proportionate increase in power consumption. The actual results indicate that motes interacting with the LOADng protocols used more energy than motes interacting with RPL, mostly because of continuous transmission modalities.

Additionally, conducting thorough and systematic analysis poses inherent challenges, especially when evaluating routing protocols. The difficulties linked to network deployments and rapid router implementations can introduce significant costs and logistical obstacles. Moreover, designing and testing real-time networks, developing network protocols, and overseeing numerous variables present complex obstacles for researchers, requiring meticulous planning and execution to navigate these challenges effectively [9].

Simulations provide the capability to accurately control various parameters, such as radio medium, transmission range, and other configurable settings within the simulators. Achieving this level of precision in real-world environments is inherently challenging due to the unpredictable variables that can impact results. The presence of these unpredictable elements causes the difficulty of experimental replication, potentially leading to inconsistent outcomes. Consequently, conducting simulations becomes necessary to evaluate performance metrics thoroughly before deploying routing protocols in real-world settings and integrating them into IoT devices.

Hence, this study analyses the performance and power consumption of three routing protocols which are RPL, AODV, and LOADng within the context of 6LoWPAN using simulation techniques. This study utilizes simulation tools to gather data on power consumption metrics, such as CPU Power, Listen Power, Transmit Power, and Total Power. The findings indicate that RPL is the most power-efficient protocol compared to AODV and LOADng. It also contributes new insights into their performance in specific simulated environments. Additionally, the study presents new comparative simulation data and visualized insights into the routing protocols, informing future testbed implementations, and potential improvements for the routing protocols in 6LoWPAN environments. The following section presents related work to this study followed by the methodology in Section 3. The results and analysis are presented in Section 4, and finally Section 5 concludes and provides recommendations for future studies in this area.

2. Related Work

6LoWPAN, an Internet Engineering Task Force (IETF) working group, specifies header compression and encapsulation techniques that allow IPv6 packets to communicate with IEEE 802.15.4 standard [10]. 6LoWPAN covers applications that need lower data rates for wireless internet connectivity. It runs in two frequency bands: 2400–2483.5 MHz internationally and 902–929 MHz in North America. With AES-128 security features, it achieves 250 kbps downlink/uplink with a range of 10–200 m [11].

The 6LoWPAN network is extremely resilient; it can self-heal and auto-configure to adjust to changing circumstances. With its mesh network, which eliminates single points of failure and supports numerous border routers for internet connectivity. Mesh network can increase overall energy consumption but marginally less than that of binary tree topology [12]. Scalability is attained by supporting up to sixteen thousand devices and thirty-two routers, which makes it appropriate for both small and big networks. In addition, 6LoWPAN has lower latency than Bluetooth and Zigbee, it is also more affordable and uses less power [13]. In the following sections, the characteristics of the three types of routing protocols which are assessed in this study are described.

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

The Internet Engineering Task Force (IETF) Routing over Low Power and Lossy (RoLL) Networks committee created RPL, a routing protocol designed for LLNs with devices with limited resources. RPL proactively optimizes routing for LLNs by applying a distance vector technique, meeting critical routing requirements over nodes with constrained resources [14,15].

A Destination Oriented Directed Acyclic Graph (DODAG) serves as the foundation for the protocol's topology [16]. Network topology setup creates a DODAG, which is uniquely recognized by a DODAG IP and RPL instance ID [17]. RPL networks directly control messages every node to identify the best parent sets to follow to reach the root, connecting with favored parents along the most effective route. Route path selection, which makes use of the ranking's idea, is crucial to RPL. In addition to identifying and preventing routing loops, ranks also let nodes distinguish between parents and siblings and allow them to keep lists of preferred parents and siblings for usage in the event of a link loss with the parent node [18]. RPL routing overhead increased in three scenarios: network topology change, additional information transmission, and speed movement of node increased [19]. Moreover, increased node mobility will result in higher energy consumption due to the need for frequent route rediscoveries [20].

For the development and upkeep of descending routes, RPL provides two operating modes: storing mode and non-storing mode. Using Destination Advertisement Object (DAO) messages delivered in unicast to selected parents, each node in the storing mode saves routes published by all other nodes in its subtree. Only the DODAG root retains the routes that are announced by every node in the network when the mode is non-storing, meaning that intermediate parents do not store downstream routes [21].

2.2. Ad Hoc On-Demand Distance Vector (AODV)

AODV is a robust and reactive routing protocol which is designed primarily for mobile ad hoc networks, originating from the work in 2003 [22]. AODV operates on-demand, activating its routing algorithm in response to specific demands within the network. The AODV routing algorithm unfolds in two distinct phases which are the control phase and the route discovery phase.

A key feature of the protocol is its utilization of a hop count-based route selection process, aiming to merge routes for efficiency and promote high bandwidth usage while minimizing data drop. However, the protocol remains cognizant of factors such as link reliability and node energy levels to ensure effective and reliable routing. AODV defines three different routing messages which function as control packets and play a crucial role in the routing process with details subsequent sections [23]. The AODV protocol executes its operations through Route Requests (RREQs), Route Replies (RREPs), Route Errors (RERRs), and HELLO messages. The HELLO message, a special case of the RREP message with TTL (Time-To-Live) set to 1, may provide local connectivity information [24]. This communication mechanism ensures the creation of linked paths between nodes in the network only when specific clusters' source nodes send arbitrary request signals.

Consequently, the AODV routing protocol relies on an on-demand nature, promoting a congestion-free system when communication is established between interconnected nodes [22]. AODV meticulously monitors and maintains each path in the network until they are acquired by the sources. Since its conceptualization in the Internet Engineering Task Force (IETF), AODV has undergone significant evolution, incorporating various improvements. The proposed variants of AODV are categorized into quality, multipath, energy, security, and routing strategy, demonstrating the protocol's adaptability and continuous refinement [24].

2.3. Lightweight On-Demand Ad Hoc Distance Vector Routing Protocol—Next Generation (LOADng)

LOADng protocol is a simplified version of AODV which focuses on 6LoWPAN. Like AODV, LOADng builds routes solely on demand. Control messages obtained from AODV allow this route development, sometimes referred to as route discovery [25]. Since LOADng is a reactive protocol, its main method of operation is to use LOADng routers to generate Route REQuests (RREQs) to find paths that go to certain destinations. The protocol calls for receiving Route REPlies (RREPs) from the destination after RREQs arrive successfully. Moreover, RREQ transfer happens at the hop-by-hop level via unicast communication [26].

As an AODV variation, LOADng and AODV use a similar method for route building, maintenance, and discovery. However, it stands out due to its optimized flooding, adaptable packet format, ease of implementation, and removal of settings that are rarely useful [26]. The destination node is tasked with determining the optimal path, which it does after obtaining several copies of the initial RREQ message. A Route Cost (RC) is carried by every duplicate of the original RREQ message, which is determined as it travels towards the destination node [27].

Routes are only created when there are data to be transmitted and a workable path to the destination exists, in line with reactive routing protocols. If traffic stays on the approved path, these pathways will be kept up. Even with its benefits, LOADng has drawbacks, like route discovery latency [8]. Unlike RPL, LOADng lacks a controlling node like a root, resulting in a single point of error. To mitigate control message overhead, LOADng employs a generalized message format [28].

2.4. Simulation Tools

In IoT area, simulators play a crucial role in replicating real-world scenarios using various quality of service (QoS) settings, enabling the prediction and mitigation of unexpected faults prior to actual deployment. It is imperative to ensure efficient management of heterogeneity in devices, technologies, settings, and applications, particularly considering the estimated 75 billion smart devices that will be connected by 2025 [29]. Realistic simulation outcomes require the capacity to disseminate information across many environments utilizing various technologies. Network Simulator tools are essential for network simulation in the context of computer networks. Large-scale network implementation and instantaneous router deployment might be costly and difficult. Setting up and experimenting with real-time networks, creating network protocols, and keeping an eye on multiple parameters provide challenges for researchers. Still, these simulators present a reasonably priced and effective substitute [9].

Cooja version 2.7 is a versatile, cross-level Java simulator, that functions within Instant Contiki 3.0 and emphasizes wireless sensor network behavior. It supports protocols under 6LoWPAN network and supports the IEEE 802.15.4 standard, which is implemented by hardware like the Texas Instrument (TI) CC2420 transceiver [30]. Emulation of hardware level motes, such as Tmote Sky, Z1 and Wireless channel models like DGRM are implemented in the simulator. Each node's radio transceiver's power condition is shown by the debugging tool TimeLine [31].

NS-2 is an open-source, discrete-event simulator that is extensively used and well-known for its ability to simulate network settings. The final official release is NS-2.35. NS-2 offers the ability to simulate network establishment, protocol implementation, and real-time scenarios. NS-2 enables users to simulate new protocols through a scripting interface. Researchers and developers will be able to explore and validate new networking protocols for real-time analysis and generate detailed trace files for performance evaluation. Being free software, NS-2 is accessible for research, development, and practical exercises on both Linux and Windows platforms [9]. It supports a variety of IP protocols, including TCP/IP, routing; however, 6LoWPAN was not supported. Conversely, NS-3 is an open-source device which was created to take the place of NS-2 for working with several protocols, such as the 6LoWPAN protocol stack [31].

NS-3, intended as a replacement for NS-2 focused on communication network research and development, in keeping with IoT goals. The latest release is NS-3.43. With optional Python bindings, the fundamental simulation is written in C++, and it is integrated with other tools such as NetAnim 3.109, PyViz 0.3.2, and Bake [30].

As desktop software, NetSim is designed for modeling and simulating diverse network types, allowing the development of user-defined protocols and integration with software like MATLAB and SUMO [9]. The current NetSim version is 14.02 with three options i.e., Academic, Pro and Standard. Recognized as an advanced simulator, NetSim is dedicated to protocol modeling and simulation of networks. It offers a comprehensive exploration of computer networks, covering most aspects of networks, making it a widely used tool in research [32].

In addition to the mentioned simulators, OMNET++, Tossim, MATLAB, and SUMO are widely used in research. OMNET++, an open-source C++ simulator for communication networks, offers packet-level analysis but it is not designed particularly for 6LoWPAN [31]. Tossim, in TinyOS, prioritizes scalability and fidelity for MicaZ motes [30]. MATLAB and Simulink support IoT system modeling with custom simulation and connectivity to platforms like ThingSpeak [9].

3. Methodology

Simulators have presented a reasonably effective substitute in setting up and experimenting with real-time networks and creating network protocols [9]. The simulation parameters need to be taken into consideration where it will be affecting the outcomes. This study implements a simulation approach to simulate the routing protocol using various settings, i.e., number of motes, mote positioning, and transmission range to obtain meaningful insight into the routing protocols' performances. We utilized Cooja for this purpose.

Unit Disk Graph Medium (UDGM), which is a radio propagation model, is selected because it is more prevalent in Cooja simulations [25,26] and aligns with the goals of this study. UDGM utilizes a defined transmission range disk whereas the inner node receives while outer ones do not. It modulates transmission power using output power comparisons and scenario distances with Packet success rates for Transmission (TX) time and Reception (RX) time as the success metrics. The simulation parameters are listed in Table 1.

Table 1. Simulation parameters.

Parameters	Scenario 1 Values	Scenario 2 Values
Simulator	Contiki 3.0/Cooja	Contiki 3.0/Cooja
Protocol	RPL, AODV, LOADng	RPL, AODV, LOADng
Data Type	UDP	UDP
Radio Propagation Model	UDGM Model	UDGM Model
Number of Motes	10, 20, 30, 40	10, 20, 30, 40
Simulation Duration	300 s	300 s
Transmission Range	50 m	100 m
Network Topology	Random, Linear, Eclipse	Random, Linear, Eclipse

Since the number of motes directly affects the performance of the motes as well as the network, it is assumed that performance metrics that are obtained after the simulation would differ. This hypothesis is based on previous academic studies [2,33] in which researchers varied the number of motes in various contexts. Changes in the number of nodes and the percentage of mobile nodes also have a gradual effect on Average Power Consumption (APC) [34]. Given that the mote counts range from 10 to 50 across various scenarios, it is posited that 40 motes are optimal for a straightforward 6LoWPAN architecture, as mentioned in ref. [5]. Consequently, the mote counts increase by increments of 10 motes for each scenario, culminating at 40 motes. Apart from the mote count, the transmission range serves as another independent variable in this study. Previous research has indicated that the transmission range can influence both power consumption and the PDR of motes [33]. It is hypothesized that power consumption will rise with an expanding transmission range since motes require increased power for signal amplification to reach more distant motes. It would be intriguing and noteworthy to examine whether varying the transmission range influences different routing protocols. Additionally, it is essential to ascertain if these protocols can function effectively or perhaps be optimized with an extended transmission range.

Consequently, the transmission range will be varied across the scenarios, specifically set at 50 m and 100 m based on findings from prior research [5]. Additionally, the simulation duration is established as 300 s, aligning with prior studies [28–32]. Employing a consistent 300 s evaluation period facilitates precise assessments of each protocol across diverse conditions and scenarios. Such consistency enables meaningful protocol comparisons and pinpoints areas warranting enhancement or optimization.

4. Results and Discussions

This study provides a comparative analysis of RPL, AODV and LOADng protocols specifically within the context of 6LoWPAN. The raw data gathered from the simulation tools including Powertrace and Collect-View were then analyzed with Python code to transfer into useful information and visualize the graph. Figure 1 provides a heatmap that offers a comprehensive analysis of mean power consumption across different scenarios, illustrating how network topology, routing protocol, transmission range, and the number of motes influence energy usage. Each cell in the heatmap represents a specific combination of these variables. The data shows different patterns across the three routing protocols and topologies to highlight the routing protocols' performance under various conditions.

Figure 1. Mean power consumption for different scenarios.

The AODV protocol consistently shows higher power consumption, particularly in denser networks and longer transmission ranges, as evidenced by the darker shades in its corresponding cells. In contrast, the LOADng and RPL protocols demonstrate more efficient power management, with lighter shades indicating lower power consumption, especially in smaller networks and shorter transmission ranges. For instance, the ring/eclipse topology with RPL protocol exhibits a significantly lower mean power consumption for 10 motes at both 100 m and 50 m, underscoring its suitability for energy-constrained environments.

These insights are crucial for optimizing network configurations in 6LoWPAN. The result is like the trends from previous research where the power consumption will be increased while the network becomes denser. The denser network is defined from the increment of the number of motes and transmission range in this research. Whenever the motes number in the network increases, the power consumption will increase as more power resources are needed from the motes to transmit packets and messages [2,5]. Other than that, the transmission range will also affect the power consumed by every node therefore the power consumed in the network simulated with a 100 m transmission range is greater than that simulated in a 50 m transmission range [33].

In addition, a pair plot provides insight into the relationship between the power as well as the trend of different powers on the type of power. Figure 2 illustrates a pair plot with different power types for various routing protocols which are RPL, LOADng, and AODV.

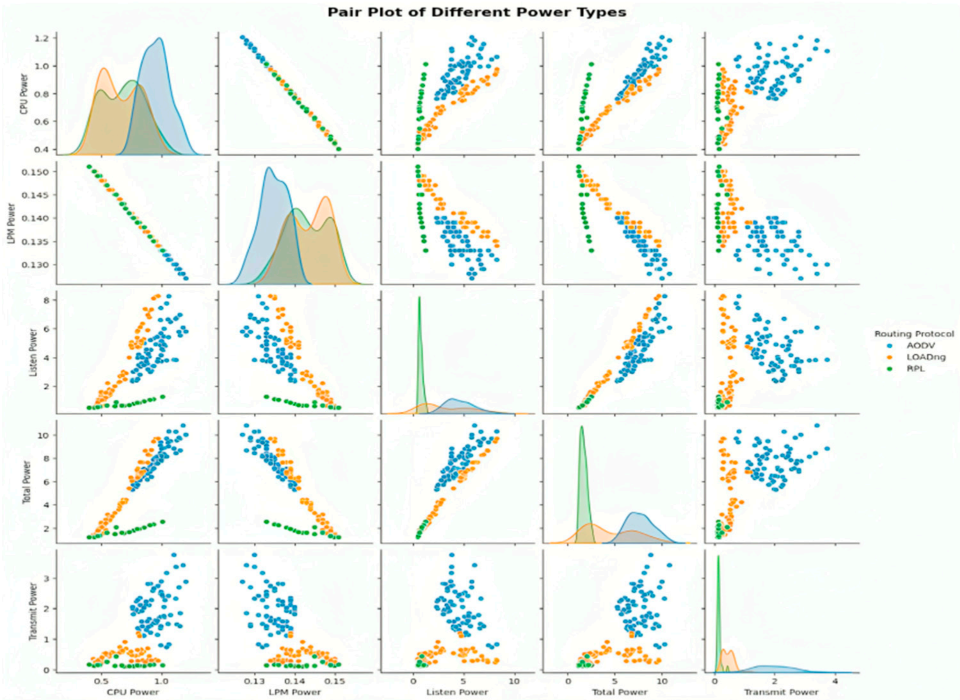

Figure 2. Pair plot of different power types.

The CPU power is positively correlated with Listen Power, Total Power, and Transmit Power. When the CPU power increases, the other mentioned power metrics tend to increase as well. CPU power shows a clear separation between the three routing protocols. The AODV and LOADng exhibit higher CPU power usage compared to RPL. In addition, LPM or Low Power Mode power shows different clusters, with RPL having the lowest values, followed by AODV and LOADng. LPM power carries an inverse relationship between LPM power and CPU power, indicating that higher CPU power corresponds to lower LPM power. LPM power shows a minor negative correlation with Listen Power, Total Power, and Transmit Power, but not as strongly as with CPU power. Moreover, the listen power demonstrates a strong positive correlation with both CPU power and Total Power. The clustering of different protocols is evident, with AODV and LOADng showing higher Listen power compared to RPL Listen power also shows a positive correlation with Transmit Power yet consists of variation. The Transmit power is positively correlated with

CPU power, Listen power, and Total power. There is a clear separation between the routing protocols, with AODV and LOADng showing higher Transmit power compared to RPL.

The pair plot shows that Transmit Power has less distinct clustering compared to other power metrics but still follows a positive trend. Overall, AODV and LOADng protocols generally consume more power across most metrics compared to RPL. RPL tends to operate at lower power levels, which may indicate better energy efficiency. The relationships among the power metrics are largely positive, indicating that power consumption in one area is typically associated with increased power consumption in others. This analysis suggests that the choice of routing protocol has a significant impact on power consumption patterns in different areas, with RPL being more energy-efficient, and AODV and LOADng requiring more power.

The investigation presents a systematic breakdown of power consumptions into components i.e., CPU Power, Listen Power, CPU Power, and Total Power consumption related to each protocol. This detailed examination reveals that power consumption increases as the number of motes rises, providing valuable insights to guide future protocol improvements focused on energy efficiency of 6LoWPAN.

5. Conclusions and Recommendations

The primary objective of this study is to investigate the performance of RPL, AODV, and LOADng routing protocols on IoT devices within the context of 6LoWPAN. Through a series of comprehensive simulations, the objective has been achieved by thoroughly analyzing and comparing the protocols' performance across various network scenarios and topologies. Our findings indicate that RPL outperforms AODV and LOADng in power efficiency, especially as network size increases empirical evidence. RPL is more suitable for scalable deployments. Its efficient DODAG maintenance mechanism enables more stable power consumption under different mote densities compared to AODV and LOADng. AODV frequent route discovery mechanism may result in higher energy consumption when higher number of motes are involved. This study contributes to a deeper understanding of the routing protocols based on empirical simulation data via the Cooja simulator. While our simulation results provide valuable insights into protocol performance, it is crucial to validate these findings through real-world testing. In addition, we assume that RPL's reliance on DODAG structures might result in lower power consumption during mobility compared to AODV. Moreover, we also assume that the energy efficiency and performance of LOADng will degrade with higher mobility. Our results suggest that RPL, which uses periodic updates to repair and maintain routes may experience higher delay or latency in mobile scenario. Hence, we recommend that future studies should advance beyond simulations by testing the routing protocols RPL, AODV, and LOADng in real-world environments using a physical testbed. The testbed can be implemented with practical scenarios, such as smart homes or smart offices with hardware like the Cortex-M3 Controller board and follow a structured methodology for configuring and testing these protocols. This approach can bridge the gap between theoretical simulations and practical implementations, ultimately advancing our understanding and application of IoT networking technologies. Hence, we plan to extend this study by incorporating advanced network performance monitoring tools to capture a broader range of performance metrics during testbed experiments. Protocol trade-offs will be investigated based on power consumption and metrics like latency, end-to-end delay, packet delivery ratio, etc. Exploring algorithmic modifications and different mobility models like Random Way Point may provide a holistic evaluation of 6LoWPAN routing protocols in high mobility environments.

Author Contributions: Conceptualization, S.F.A.R.; investigation, P.S.C., N.H.K. and M.F.A.; methodology, P.S.C., N.H.K. and M.F.A.; resources, S.Y.; supervision, S.F.A.R.; validation, S.Y. and W.Y.; writing—original draft, P.S.C. and S.F.A.R.; writing—review and editing, S.F.A.R. and N.H.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: All authors would like to thank the Centre for Intelligent Cloud Computing for the encouragement and support in completing this study. The authors acknowledge the use of Quillbot (free web version) in the process of correcting the grammar and improving the clarity as well as quality of the English language in this manuscript. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare there are no conflicts of interest. All authors agree to the final version of the manuscript.

References

1. Srinivasa, A.H.; Siddaraju. Performance analysis of IoT routing protocol: A study. *Int. J. Eng. Trends Technol.* **2021**, *69*, 102–106. [CrossRef]
2. Syahputra, R.; Siregar, R.A.; Kartikasari, D.P. Studi Penggunaan Energi pada Implementasi Protokol Routing RPL dan LOADng di Wireless Sensor Network. *Jurnal Pengembangan Teknologi Informasi dan Ilmu Komputer* **2019**, *3*, 4092–4101.
3. Zainaddin, D.A.; Hanapi, Z.M.; Othman, M.; Zukarnain, Z.A.; Abdullah, M.D.H. Recent trends and future directions of congestion management strategies for routing in IoT-based wireless sensor network: A thematic review. *Wirel. Netw.* **2024**, *30*, 1939–1983. [CrossRef]
4. Essop, I.; Ribeiro, J.C.; Papaioannou, M.; Zachos, G.; Mantas, G.; Rodriguez, J. Generating Datasets for Anomaly-Based Intrusion Detection Systems in IoT and Industrial IoT Networks. *Sensors* **2021**, *21*, 1528. [CrossRef] [PubMed]
5. Hayati, N.; Yusoff, B.M.; Azma, N.; Zakaria, B. Analysis of RPL Power Consumption in 6LoWPAN Ecosystem using COOJA Simulator. *J. Adv. Comput. Technol. Appl. (JACTA)* **2019**, *1*, 1.
6. Ching, T.W.; Aman, A.H.M.; Azamuddin, W.M.H.; Sallehuddin, H.; Attarbashi, Z.S. Performance Analysis of Internet of Things Routing Protocol for Low Power and Lossy Networks (RPL): Energy, Overhead and Packet Delivery. In Proceedings of the 2021 3rd International Cyber Resilience Conference (CRC), Virtual, 29–31 January 2021; pp. 1–6.
7. Khlaifi, H.; Zrelli, A.; Ezzedine, T. Routing Protocols for A Border Monitoring Application. In Proceedings of the 2019 International Conference on Internet of Things, Embedded Systems and Comsmunications (IINTEC), Tunis, Tunisia, 20–22 December 2019; pp. 1–6.
8. Glissa, G.; Meddeb, A. 6LowPSec: An end-to-end security protocol for 6LoWPAN. *Ad Hoc Netw.* **2019**, *82*, 100–112. [CrossRef]
9. Ojha, T.; Misra, S.; Raghuwanshi, N.S. Internet of Things for Agricultural Applications: The State-of-the-art. *IEEE Internet Things J.* **2021**, *8*, 10973–10997. [CrossRef]
10. Akbar, M.S.; Hussain, Z.; Sheng, M.; Shankaran, R. Wireless Body Area Sensor Networks: Survey of MAC and Routing Protocols for Patient Monitoring under IEEE 802.15.4 and IEEE 802.15.6. *Sensors* **2022**, *22*, 8279. [CrossRef]
11. Famá, F.; Faria, J.N.; Portugal, D. An IoT-based interoperable architecture for wireless biomonitoring of patients with sensor patches. *Internet Things* **2022**, *19*, 100547. [CrossRef]
12. Alghofaili, R.; Albinali, H.; Azzedin, F. Build–Launch–Consolidate Framework and Toolkit for Impact Analysis on Wireless Sensor Networks. *J. Sens. Actuator Netw.* **2024**, *13*, 17. [CrossRef]
13. Khattak, S.B.A.; Nasralla, M.M.; Farman, H.; Choudhury, N. Performance Evaluation of an IEEE 802.15.4-Based Thread Network for Efficient Internet of Things Communications in Smart Cities. *Appl. Sci.* **2023**, *13*, 7745. [CrossRef]
14. Koutras, D.; Stergiopoulos, G.; Dasaklis, T.; Kotzanikolaou, P.; Glynos, D.; Douligeris, C. Security in IoMT Communications: A Survey. *Sensors* **2020**, *20*, 4828. [CrossRef]
15. Hashemi, S.Y.; Aliee, F.S. Fuzzy, Dynamic and Trust Based Routing Protocol for IoT. *J. Netw. Syst. Manag.* **2020**, *28*, 1248–1278. [CrossRef]
16. Almusaylim, Z.A.; Alhumam, A.; Jhanjhi, N. Proposing a Secure RPL based Internet of Things Routing Protocol: A Review. *Ad Hoc Netw.* **2020**, *101*, 102096. [CrossRef]
17. Arena, A.; Perazzo, P.; Vallati, C.; Dini, G.; Anastasi, G. Evaluating and improving the scalability of RPL security in the Internet of Things. *Comput. Commun.* **2020**, *151*, 119–132. [CrossRef]

18. Verma, A.; Ranga, V. Security of RPL Based 6LoWPAN Networks in the Internet of Things: A Review. *IEEE Sens. J.* **2020**, *20*, 5666–5690. [CrossRef]
19. Yusoff, N.H.M.; Azma, N.; Hidayat, A. Design and implementation of 6LoWPAN application: A performance assessment analysis. *Int. J. Adv. Comput. Sci. Appl.* **2020**, *11*, 262–269. [CrossRef]
20. Heidari, A.; Amiri, Z.; Jamali, M.A.J.; Jafari, N. Assessment of reliability and availability of wireless sensor networks in industrial applications by considering permanent faults. *Concurr. Comput. Prac. Exp.* **2024**, *36*, e8252. [CrossRef]
21. Airehrour, D.; Gutierrez, J.A.; Ray, S.K. SecTrust-RPL: A secure trust-aware RPL routing protocol for Internet of Things. *Futur. Gener. Comput. Syst.* **2019**, *93*, 860–876. [CrossRef]
22. Zrelli, A. Hardware, Software Platforms, Operating Systems and Routing Protocols for Internet of Things Applications. *Wirel. Pers. Commun.* **2021**, *122*, 3889–3912. [CrossRef]
23. Manikannan, K.; Nagarajan, V. Optimized mobility management for RPL/6LoWPAN based IoT network architecture using the firefly algorithm. *Microprocess. Microsyst.* **2020**, *77*, 103193. [CrossRef]
24. Saini, T.K.; Sharma, S.C. Recent advancements, review analysis, and extensions of the AODV with the illustration of the applied concept. *Ad Hoc Netw.* **2020**, *103*, 102148. [CrossRef]
25. Sobral, J.V.V.; Rodrigues, J.J.P.C.; Rabêlo, R.A.L.; Saleem, K.; Furtado, V. LOADng-IoT: An Enhanced Routing Protocol for Internet of Things Applications over Low Power Networks. *Sensors* **2019**, *19*, 150. [CrossRef]
26. Yang, G.; Jan, M.A.; Rehman, A.U.; Babar, M.; Aimal, M.M.; Verma, S. Interoperability and Data Storage in Internet of Multimedia Things: Investigating Current Trends, Research Challenges and Future Directions. *IEEE Access* **2020**, *8*, 124382–124401. [CrossRef]
27. Lavenu, C.; Chauvenet, C.; Treffiletti, P.; Varesio, M.; Hueske, K. Standardization Challenges, Opportunities and Recent Evolutions for the G3-PLC Technology. *Energies* **2021**, *14*, 1937. [CrossRef]
28. Swathi, G.C. Collaborative Attack Effect on Routing Protocols in IoT: A Performance Analysis. *J. Mech. Contin. Math. Sci.* **2020**, 132–139. [CrossRef]
29. Patel, B.; Shah, P. Direct Neighbour Sink Reputed Trust Based Intrusion Detection System to Mitigate Sinkhole Attack in RPL for IoT Networks. *J. Eng. Sci. Technol. Rev.* **2021**, *14*, 38. [CrossRef]
30. Patel, B.; Shah, P. Simulation, modelling and packet sniffing facilities for IoT: A systematic analysis. *Int. J. Electr. Comput. Eng. (IJECE)* **2020**, *10*, 2755–2762. [CrossRef]
31. Al-Kashoash, H.A.A.; Kharrufa, H.; Al-Nidawi, Y.; Kemp, A.H. Congestion control in wireless sensor and 6LoWPAN networks: Toward the Internet of Things. *Wirel. Netw.* **2018**, *25*, 4493–4522. [CrossRef]
32. Tom, R.J.; Sankaranarayanan, S.; de Albuquerque, V.H.C.; Rodrigues, J.J.P.C. Aggregator based RPL for an IoT-fog based power distribution system with 6LoWPAN. *China Commun.* **2020**, *17*, 104–117. [CrossRef]
33. Sanila, A.; Mahapatra, B.; Turuk, A.K. Performance Evaluation of RPL protocol in a 6LoWPAN based Smart Home Environment. In Proceedings of the 2020 International Conference on Computer Science, Engineering and Applications (ICCSEA), Gunupur, India, 13–14 March 2020; pp. 1–6.
34. Hkiri, A.; Alqurashi, S.; Ben Bahri, O.; Karmani, M.; Faraj, H.; Machhout, M. Performance Evaluation of Mobile RPL-Based IoT Networks under Hello Flood Attack. *Electronics* **2024**, *13*, 2226. [CrossRef]