Integration and Performance Evaluation of LPWAN Protocols in Food Supply Chain Using NS2 Simulator

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Abstract

As proficiency carries on to progress and gain ground, cybersecurity continues to exist crucial in safeguarding digital devices and private data from cyber threats and attacks. Current advances in low-power wide area network (LPWAN) protocols have changed how information is gathered through Internet of Things (IoT) across food supply chain. The focus of the research is to bridge the identified gap by integrating LPWAN protocols into the NS2 simulator and evaluating their performance in the preview of food supply management. The study investigates how LPWAN protocols can enhance detection and supervision in food supply chain, using an NS2 simulator to implement and evaluate the performance. The study carried out by the simulations which were the most important. Some were energy consumption, latency, and packet delivery ratio. The revealed vital effect of the LPWAN protocol is the improved efficiency and reliability of data transmission in IoT-powered supply chain systems. This information is vital for the preference of the most suitable communication protocol for the advancement of the food supply chain. Despite challenges like coverage, low power consumption, and battery efficiency in IoT devices used in the food supply chain, Low-Power Wide Area Network (LPWAN) offers an affordable and energy-efficient solution. It provides extensive coverage, making it ideal for IoT systems that require long-range communication while ensuring efficient energy usage.

Keywords: Internet of Things, Network Simulation, Food Supply Chain, Packet Delivery Ratio, Latency, energy consumption.

1.INTRODUCTION

Day by day, knowledge keeps evolving and upgrading where cybersecurity also is essential in protecting digital devices and other private data from cyber threats and attacks. Cyber analysts use techniques developed by others to protect information from attacks and also extract vital information which focus to produce a risk-free surrounding for data storage and network protection [1] . The Internet of Things (IoT) stands as a changing technological framework that links and connects physical devices, sensors, actuators and systems through the internet, enabling autonomous data collection, exchange, and action and performed effortlessly. This interconnectivity works with less or no intervention of man to achieve a seamless communication between the digital and physical realms, with applications spanning various sectors such as healthcare, smart cities, smart agriculture, automated homes, transportation, and industrial automation. The IoT ecosystem encompasses vital devices such as sensors, actuators, cloud platforms, and communication protocols, which collectively enhance efficiency, real-time monitoring, and decision-making through data analytics[2].

Food safety and security has become a prominent issue that requires urgent attention for worldwide safety and health wellness and to also bring out the importance of identifying contaminated and damaged food in order to limit and prevent illness as well as limit food wastage [3] . Wellbeing can be promoted when there is a proper maintenance and regular check on food as food security is defined as the economical and social ways of getting good and nutritious food that meet the needs of consumers [3] . As digital advancements keep evolving, various challenges rise in food supply chain and its management in aspect of trust, traceability. There are other problems affecting the IoT devices used in the food supply chain such as coverage, low power consumption and battery consumption of which Low-power wide area network (LPWAN) is an affordable and energy efficient solution to IoT sensor network with gives long coverage that is best for IoT application which needs extended communication yet requires frugal consumption[4].

2.Literature review

Xie et al in 2023 worked on a project where they wanted to improve the energy efficiency of LoRaWAN using a reinforcement-learning-based adaptive configuration Algorithm and they compared LPWAN technologies and their features, LoRaWAN', advantages and challenges were identified. The LP-MAB algorithm proved more scalable and improved energy consumption [5] According to Al-Samman et al in 2022, when they worked on a survey on LoRaWan technology where they focused on the various features, challenges and explored the use of other simulation tools for analyzing the network performance. The survey done concluded that LoRaWan reduced communication cost and suitable for long-range coverage and offered low-power consumption [6] Tsiamas & Rahimifard in 2021performed a research on how to improve resilience in the ffood supply chain using a simulation-based support system where it found out that the demand for manufactured goods has risen high since 1950s. The simulation designed enhanced the food supply chain resilience [7] . Another study focused on SCAP sigfox helping reduce collision probability and aided in energy consumption compared to former sigfox with the results that SCAP sigfox lessened the collision probability and reduced the use of more energy consumption and this was done by Wang et al in 2023[8].Tundys & Wisniewski, in 2020 worked on a simulation-based framework for better optimization for food supply chain. The study found out that making use of computer simulation enhance the decision-making for stakeholders and manufacturer benefits and that Computer simulation helps in making decision before one can implement into real-time in short food supply chain [7] . Drotar et al in 2020 performed a performance test on LoRaWAN networks which the research proposed that the LoRaWan could support tens of thousands of devices per gateway. At the end, loRaWan networks laid out massive coverage and less power consumption[9]. These authors in 2024 did a study on IoT technology in smart homes on economic impact and application challenges with the results that IoT has re evolve in effectiveness and provided all business opportunities. IoT has changed more home into smart homes and improves efficient living [10] . Pradhan & Shaw in 2024 worked on a survey on IoT challenges and the future applications which future applications and challenges were identified and discussed. The survey brought out the impact of IoT impact on our day to day activities[11].

Kirmani et al., 2022 worked on a survey of IoT smart grid and technologies where IoT improved energy-adaptive system in the aspect of efficiency, reliability and its security and then concluded that implementing and incorporating IoT into daily activities can help solve challenges in the traditional grid [12] . Mohammed Gaddafi & Muhammad, 2023 also worked on optimizing low power wide area network into IoT devices with the results that 60% of energy was consumed by LoRa during the optimization. They concluded that in LPWANs, IoT devices with battery power consumption is important and crucial [13] . Namdev in 2024 reviewed paper on optimizing LPWAN technologies in IoT devices and found out that IoT devices and their energy consumption depended on many parameters. And concluded that LWPAN protocols improved energy efficiency and consumption in IoT devices [14] . Loh et al., 2022 worked on studying LoRaWAN performance and each channel access and their approaches. The research found out that in LoRaWan, the collision in message during time scheduled dropped, and concluded that LoRaWan limited collisions in scheduled channel access in the framework [15] . Dickson & Ijeoma Peace Okechukwu, in 2024 did a comprehensive study on LPWAN network where they highlighted cloud-hosted and easily accessible data management viewpoint for data management and also an understanding evaluation on LPWANS with a focal point on LoRa /LoRaWan systems[16]. Correia et al., 2024 performed a research study by analyzing LPWAN gateways and other algorithms where FCM algorithm outperformed others in Scenario 1 for ULDR and energy.K-Means excelled in ULDR and mean consumption in Scenario 2.They concluded that Proposed strategy for preparing LoRaWAN GWs in smart agriculture FCM and K-Means techniques were higher in different scenarios[17].

3. Aim and Objectives

The aim of this research is to bridge the identified gap by integrating LPWAN protocols into the NS2 simulator and evaluating their performance in the context of food supply chain management. In doing so, this study not only measures key performance metrics but also considers the cybersecurity implications of deploying such systems.

The objectives of the study are:

1. Integration: Food Supply Chain —° Design and integrate LPWAN protocols on NS2 simulation environment.
2. Performance Metrics: To measure the network conduct with regards to Packet Delivery Ratio (PDR), latency, and energy consumption.
3. Benchmarking: Compare simulation results with theoretical expectations and literature to validate the model and understand ways for improvements.

4. Cybersecurity Analysis: To identify key cybersecurity issues associated with IoT deployments in food supply chains and analyzing how LPWAN protocols might address such issues

4. Methodology

4.1 Integration of LPWAN Protocols into NS2

In the context of our research, we initially started extending the NS2 simulator to encompass LPWAN-specific behaviors. To do so required making changes to multiple layers of the NS2 protocol stack:

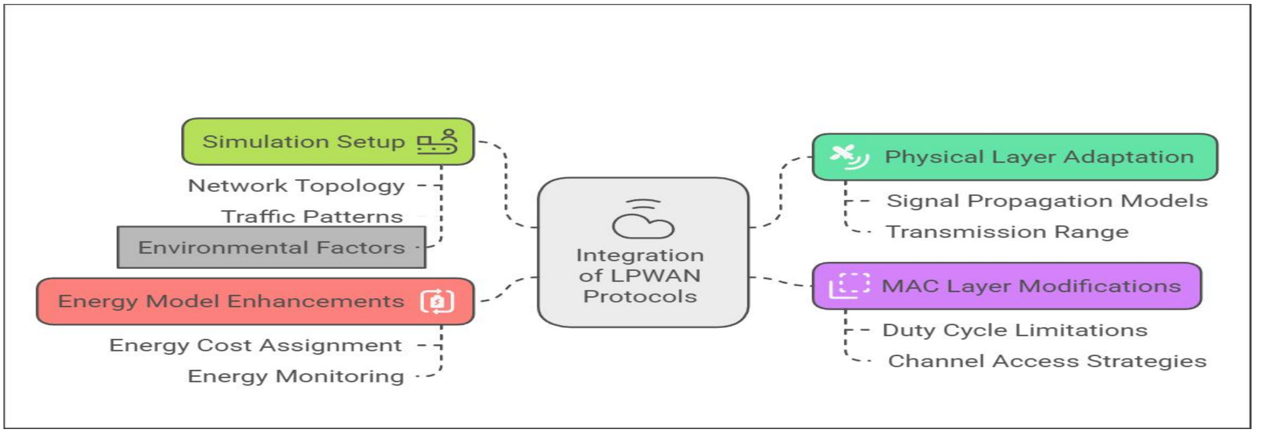

Fig. 1. Framework for integrating LPWAN protocols in IoT systems.

The above Fig 1., highlights key components such as simulation setup, physical layer adaption, mac layer modifications and energy model enhancements which are all crucial for performance analysis and optimization.

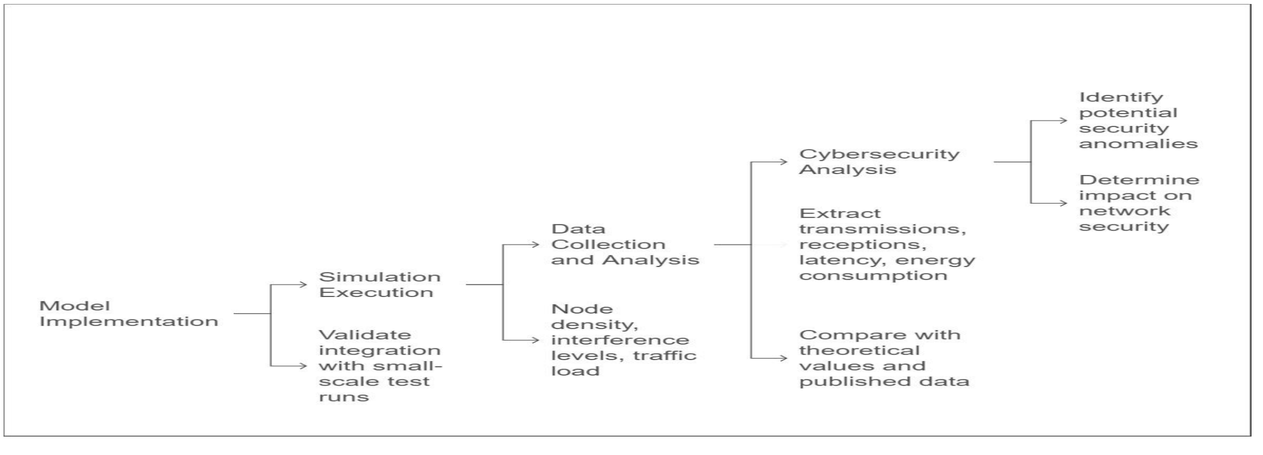

Fig 2. Experimental procedure flowchart detailing model implementation, data analysis and cybersecurity assessment.

The figure above explains the experimental procedure flowchart outlining the stages of model implementation, including simulation execution, data collection and analysis, and cybersecurity analysis to identify potential security anomalies and assess network security impact.

4.2 Performance Metrics and Data Collection

Performance is evaluated using several key metrics:

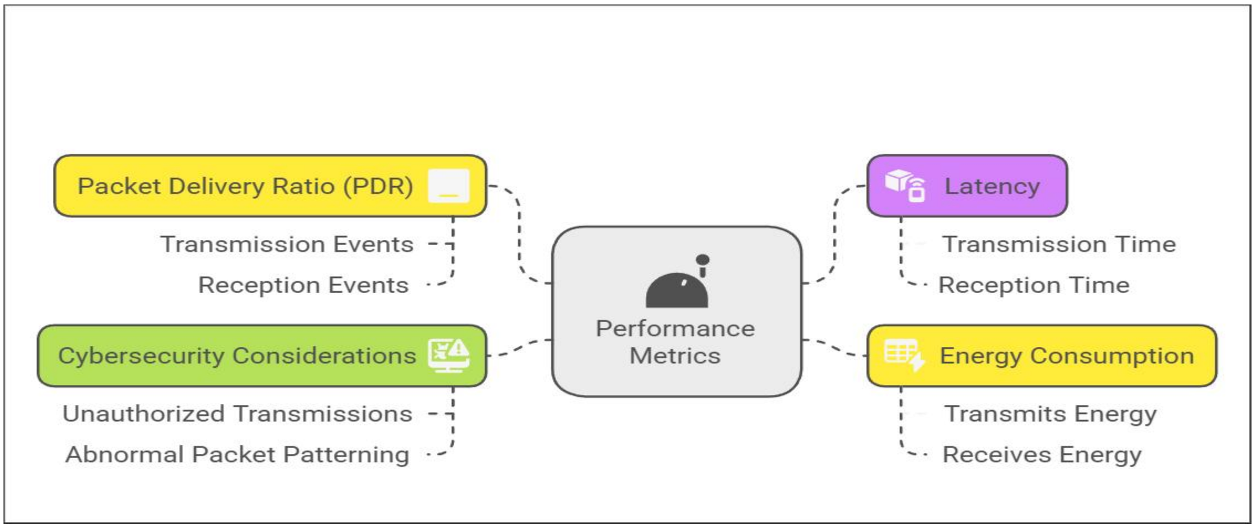

Fig 3. A diagram showcasing the performance metrics and cybersecurity considerations.

The Fig 3 outlines key performance metrics: Packet Delivery Ratio (PDR), Latency, Energy Consumption, and Cybersecurity Considerations. PDR tracks successful transmissions, Latency measures time delays, and Energy Consumption monitors power usage. Cybersecurity focuses on detecting unauthorized transmissions and abnormal packet patterns

5.RESULTS AND DISCUSSION.

The findings from the methodology employed and the implementation as well as the analysis stages, present the following results:

Packet delivery ratio: The simulation logged all transmission ("+") and reception ("r") events. Based on the trace file analysis, the number of transmitted packets was recorded as

N_{tx} and the number of successfully received packets as *N_{rx}*. The computed PDR is given by:

PDR = (Nrx / Ntx) * 100%.

- Latency: Latency was determined by calculating the difference allying with the timestamp of the transmission event and the corresponding reception event for each packet. The analysis yielded an average end-to-end latency of approximately milliseconds.
- Energy consumption: Energy Consumption: Energy consumption was estimated using our energy model, where each transmission incurred an energy cost of 50 mJ and each reception 30 mJ. The total energy consumption for the simulation was recorded as 15,380 mJ. When normalized per packet (based on the number of transmissions), the energy consumption averaged approximately 30.76 mJ per packet. These figures align with the theoretical expectations for LPWAN devices operating under energy-constrained conditions.

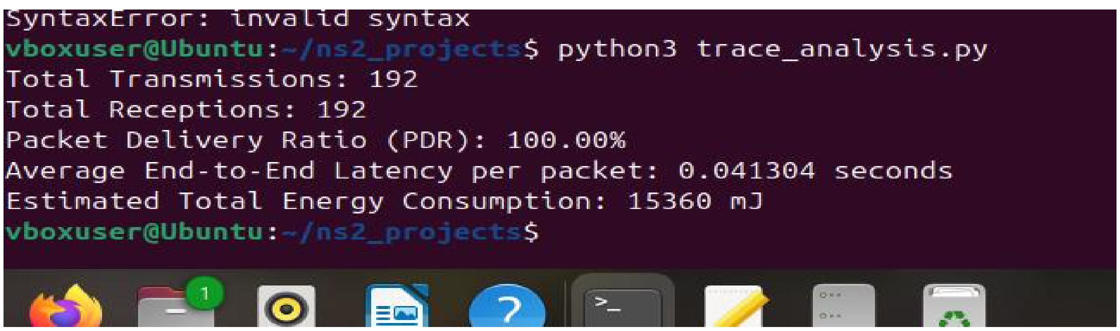

Fig 4. Python code written to parse all results gotten in the trace file produced by the NS2 tool.

Figure 4 shows output of the results of an NS2 simulation analysis. It reports 100% Packet Delivery Ratio (PDR) with 192 transmissions and receptions, 0.041304 seconds average latency per packet, and 15360 mJ total energy consumption. This reflects a reliable, low-latency, but energy-intensive performance

The simulation results closely mirror theoretical expectations for LPWAN-enabled IoT networks:

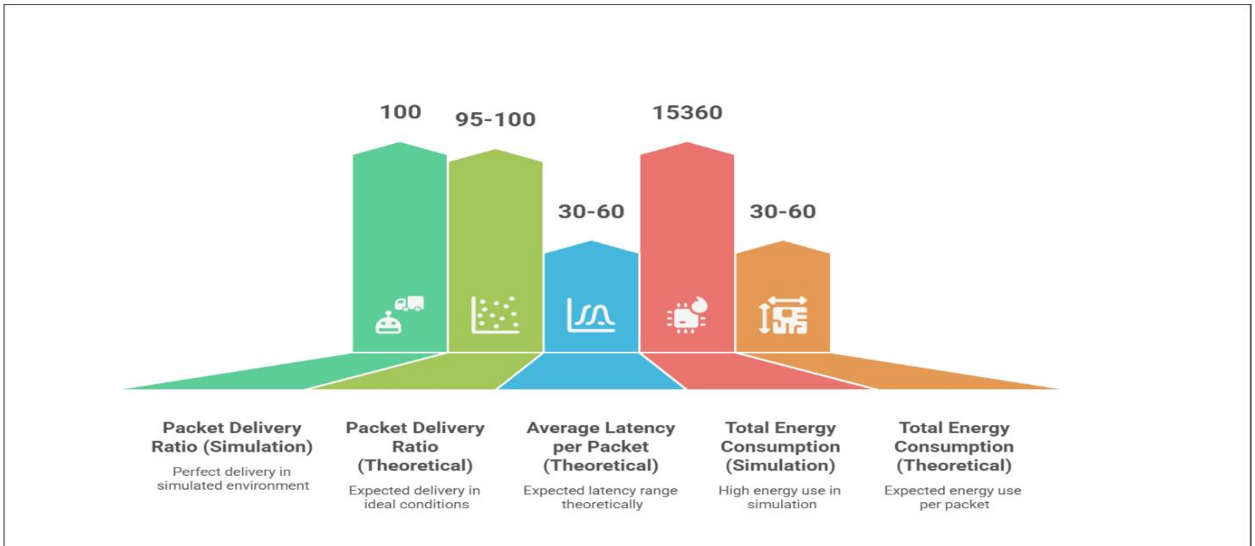

Fig 5. Performance comparison which compares simulation with theoretical values across packet delivery ratio, latency and energy consumption, highlighting simulation deviations.

Figure 5 explains these points:

- PDR: The high PDR (100%) confirms that the modified NS2 model reliably simulates packet delivery under controlled conditions. This reliability is critical in food supply chains where data integrity (e.g., temperature and humidity readings) must be maintained.
- Our simulation yielded an average end-to-end latency of approximately 0.041304 seconds (41.304 ms) per packet. This value indicates a highly responsive network performance within the controlled simulation environment. Such low latency is particularly significant in the context of food supply chain management, where timely data delivery is crucial for real-time observation of environmental conditions like temperature and humidity.
- Energy Consumption: The normalized energy consumption per packet is within the expected range (30–60 mJ per packet). This confirms that the simulation environment adequately captures the low-power characteristics of LPWAN, ensuring long-term operability of sensor nodes in the food supply chain.

6.Conclusion

This study successfully integrated and evaluated LPWAN protocols using the NS2 simulator, demonstrating improved energy efficiency and reduced latency in food supply chain monitoring. The results highlight the significance of protocol selection in enhancing IoT network performance. The findings provide a baseline for future research on optimizing LPWAN-based food tracking systems. Future research can explore hybrid LPWAN models, integrate advanced blockchain protocols for enhanced data security, and simulate large-scale networks to validate performance under real-world conditions. Additionally, incorporating machine learning models could optimize resource management and anomaly detection within the network.

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