Design, Implementation, and Comparative Study of LORA and WSN Data Transmission for Solar Smart Streetlight Monitoring

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Design, Implementation, and Comparative Study of LORA and WSN Data Transmission for Solar Smart Streetlight Monitoring

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Abstract: *This study explored and compared two wireless communication systems—LoRa-based (RFM95W) and WSN-based (nRF24L01)—for monitoring solar-powered smart streetlights. LoRa, operating at 915 MHz, was tailored for long-range, low-power communication, making it well-suited for remote or rural areas. Meanwhile, the WSN system, running at 2.45 GHz, proved more effective in short-range, high-density environments. Coverage simulations using MATLAB were confirmed through field tests at Caraga State University with real sensor data. The performance evaluation focused on packet delivery ratio (PDR), latency, data accuracy, throughput, and network capacity. LoRa achieved a higher PDR of 76.92% and demonstrated better scalability. On the other hand, WSN offered faster response times (24.5 ms), greater throughput (979.59 bps), and improved accuracy (75.00%). Economically, WSN also had a higher internal rate of return (7285%) and benefit-cost ratio (₱588.12). Overall, the findings suggest LoRa is ideal for wide-area deployments, while WSN excels in fast, accurate, and cost-efficient applications.*

Keywords: LoRa; WSN; Smart Streetlight; Data Transmission; Wireless Communication

1. INTRODUCTION

Although they were essential for maintaining public safety and visibility, traditional street lighting systems had a number of drawbacks, such as manual operation, high energy consumption, and costly maintenance needs. High-intensity discharge (HID) lamps, like sodium vapor lamps, were used in these systems, which usually ran on set schedules and increased carbon emissions and operating costs. Smart street lighting systems were created to get around these restrictions by combining sensors, artificial intelligence (AI), and the Internet of Things (IoT) [1]. These developments greatly increased energy efficiency and decreased consumption by enabling dynamic brightness adjustment based on real-time inputs like traffic flow and weather conditions [2].
LoRa (Long Range) technology offered a promising solution through its low-power, long-range communication capabilities, making it particularly suitable for remote or rural environments. It proved especially valuable in geographically isolated and disadvantaged areas (GIDA), where infrastructure and maintenance support were limited [3,4,5]. LoRa enabled remote monitoring without relying on cellular networks, effectively addressing the high operational costs and accessibility challenges common in GIDA [6,7]. Its proven success in applications like boat tracking and photovoltaic plant monitoring further highlighted its effectiveness in energy management and cost-efficient data collection [8].
On the other hand, WSN (Wireless Sensor Network)-based systems were better suited for dense urban environments. These systems utilized localized, multi-hop communication technologies such as 433 MHz RF modules and IPv6 addressing to enhance streetlight control [9,10]. They supported adaptive dimming strategies capable of reducing energy usage by up to 70%. This study aimed to conduct a comparative analysis of LoRa and WSN technologies in the context of solar-powered smart streetlight systems, with the objective of identifying the most effective, reliable, and cost-efficient solution to advance the goals of sustainable development and energy conservation.

2. MATERIALS AND METHODS

2.1 System overview

The framework for the proposed communication systems for solar-powered streetlight monitoring was illustrated in Fig. 1. This framework showcased the direct signal transmission and reception from the monitoring nodes to the central gateways, ensuring effective data propagation over designated distances using established parameters. This structure served as the foundation for the methodology employed in the study.
The study aimed to develop and compare two solar-powered streetlight monitoring systems: one using a LoRa-based (RFM95W) module for long-range communication, and the other using a WSN-based (NRF24L01) module for short-range communication. Both systems used ESP32 microcontrollers to collect sensor data and transmit it to a central gateway (TTGO T-CALL ESP32), which received the data and could forward it to a cloud server for real-time monitoring.

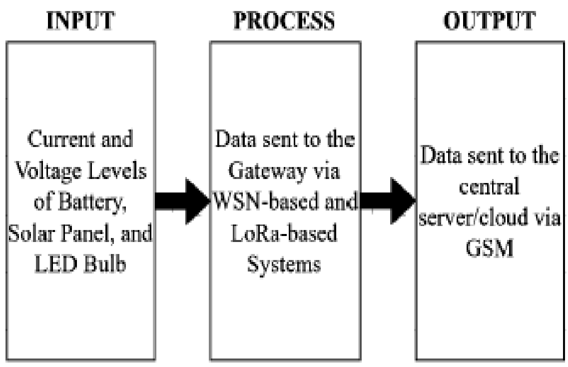

Fig. 1. Framework of the study

2.2 System design and development

The system flowchart outlines the operational process of each system, from data collection to transmission.

Fig. 2 shows the WSN-based system flowchart, it demonstrates data transmission using NRF24L01, which operates on a 2.4 GHz frequency. The process starts with system initialization, where each streetlight nodes generate and store data.

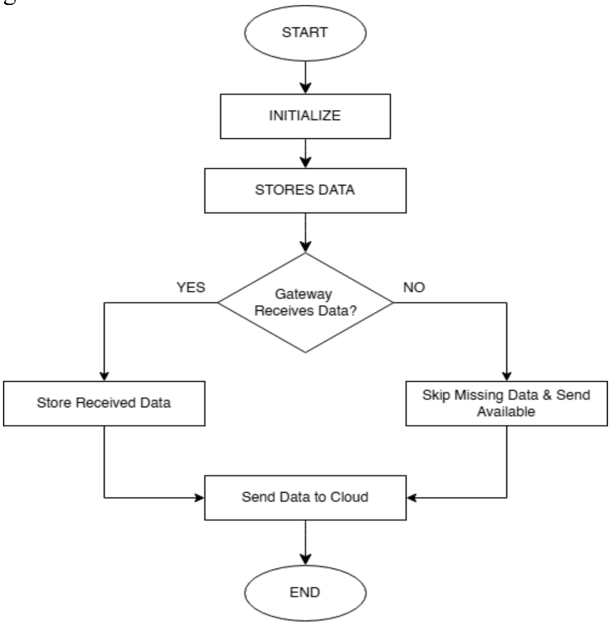

Fig. 2. WSN-based system flowchart

The gateway system then checks if it has received data from each streetlight nodes. If data is missing, the system skips unavailable data and transmits only the received information. The Gateway then forwards and upload the collected data to the Cloud. Unlike LoRa, the WSN-based system is better suited for small-scale applications due to its shorter communication range. It prioritizes real-time data transmission, ensuring that even in cases of missing data, the system still sends the available information.

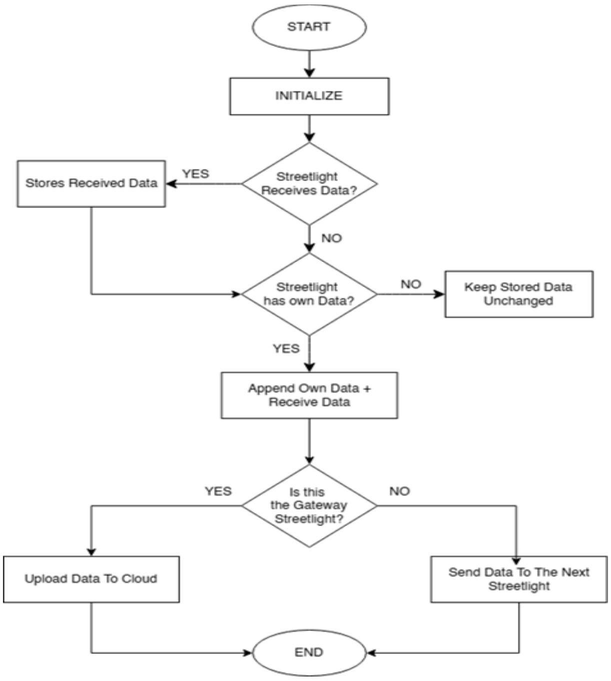

Fig. 3. LoRa-based system flowchart

On the other hand, Fig. 3 shows the Lora-based system flowchart, it represents how data is transmitted through a network of streetlights using LoRa communication. The process begins with system initialization, where each streetlight node checks if it has received data from another node. If data is received, it is stored; otherwise, the system verifies whether the streetlight has its own sensor data. If so, it appends the new data to the existing one before forwarding it to the next streetlight. This process continues until the data reaches Gateway Streetlight, which is responsible for uploading the collected data to the cloud for remote monitoring. This system is highly scalable, supports long-range communication, and ensures efficient data transmission across multiple nodes.

2.3 System 3D design

This section provides a visual representation of the actual hardware setup, ensuring proper integration of all components before physical assembly. The 3D model helps in visualizing the layout, optimizing space, and ensuring efficient cable management.

Fig. 4 illustrates the 3D design of WSN-based systems, showing the arrangement of electronic components, the antenna placement for optimal signal transmission, and the positioning of power sources for efficient energy distribution. It also includes the placement of NRF24L01 transceivers, ESP32 microcontrollers, TTGO T-CALL ESP32 gateways, battery power sources, and voltage regulators. The layout ensures minimal signal interference and stable power flow to each component during operation. Additionally, the compact and modular design facilitates ease of maintenance and potential scalability for future system expansions.

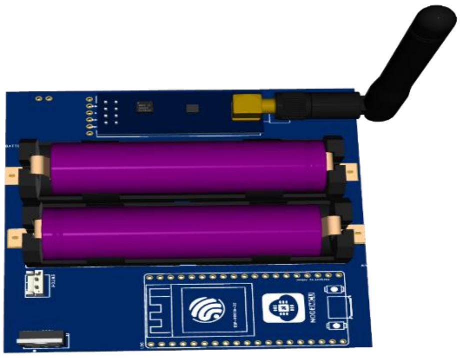

Fig. 4. 3D Model for LoRa-based System

Fig. 5 illustrates the 3D design of the LoRa-based system, highlighting the arrangement of electronic components. The design includes the integration of LoRa (RFM95W) modules, ESP32 microcontrollers, TTGO T-CALL ESP32 gateways, battery units, and voltage regulators.

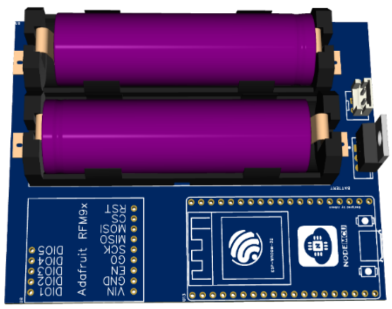

Figure 5. 3D Model for WSN-based System

2.4 System physical design

This section presents the physical layout and integration of the hardware components used in both the WSN-based and LoRa-based systems. The design ensures compactness, durability, and power efficiency suitable for outdoor deployment. Visual documentation of the assembled.

Fig. 6 illustrates the physical implementation of the WSN-based system, which includes the NRF24L01 transceiver module, ESP32 microcontroller, voltage regulator, and lithium-ion battery pack. The NRF24L01 antenna is positioned vertically for optimal signal propagation in short-range communication. The overall design is lightweight and modular, allowing quick deployment in urban or campus settings where space and efficiency are prioritized.

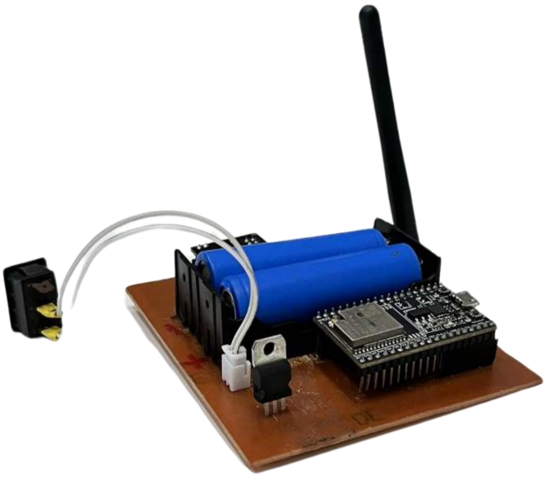

Fig. 6. Physical design of WSN-based System

Fig. 7 shows the actual assembled LoRa-based system, highlighting the integration of the RFM95W LoRa module with the ESP32 microcontroller, power supply unit, and external antenna. The antenna is mounted externally to maximize signal range. This setup supports long-distance data transmission suitable for geographically isolated and disadvantaged areas (GIDA).

Fig. 7. Physical design of LoRa-based System

2.5 System Evaluation and Data Analysis

This study evaluates the performance and feasibility of LoRa-based and (WSN)-based systems through a structured testing and analysis framework. The evaluation assesses key performance indicators such as communication range, data reliability, signal quality, latency, scalability, and cost-effectiveness. Both systems are tested in controlled environments by transmitting messages at varying distances and analyzing results including message reception status, signal strength (RSSI), signal-to-noise ratio (SNR), and transmission latency *(LoRa.packetRssi()* and *LoRa.packetSnr()*).

Performance analysis uses standard metrics: Packet Delivery Ratio (PDR) for reliability, data reception accuracy for efficiency, and latency, throughput, and network capacity to assess scalability and real-time monitoring. Throughput is measured by the total data received over time, and network capacity is evaluated by multiplying throughput per node by the number of nodes. Lower latency indicates better suitability for real-time applications.

Additionally, the study incorporates a cost-effectiveness analysis using financial indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), Benefit-Cost Ratio (BCR), and Payback Period. These metrics provide a data-driven comparison of long-term economic viability, ensuring the chosen system meets both technical and financial sustainability requirements.

3. RESULTS AND DISCUSSION

This section presents the evaluation results of the LoRa-based and WSN-based data transmission systems developed for solar smart streetlight monitoring. The performance of both systems was analyzed based on the data collected during field tests, focusing on their scalability, reliability, cost-effectiveness, and real-time monitoring capabilities. A comparative analysis was carried out to determine the more suitable system for specific deployment scenarios. The findings offer insights into the strengths and limitations of each system and their potential implications for future implementation.

In terms of communication range and data reception, both systems were tested within the Caraga State University (CSU) main campus. The LoRa-based system demonstrated stable and efficient performance, with uninterrupted data transmission achieved up to 500 meters. Between 500 to 700 meters, the system continued to receive data; however, occasional packet loss was observed. Beyond 700 meters, the system’s performance declined, and at 800 meters and beyond, communication could no longer be established. These results indicated that the LoRa-based system was well-suited for mid-range applications in semi-obstructed environments, such as university campuses or distributed infrastructure layouts. The findings emphasized the system’s potential for cost-effective and scalable deployment in rural and semi-urban settings where long-range communication is essential.

Table 1. LoRa-based system data reception

Distance (A→B)	100m	250m
Distance (B→C)	100m	100m
Status (A→B)	✓	✓
Status (B→C)	✓	✓
Status (A data at C via Node B)	✓	✓
RSSI (dBm)	-64	-70
SNR (dBm)	10.5	8.3
Latency (ms)	118	133

The WSN-based system demonstrated effective short-range communication during testing at the Caraga State University campus. As shown in Table 2, the system maintained reliable data transmission up to 400 meters, with latency values ranging from 13 to 23 milliseconds, which indicated fast and responsive performance. At 500 meters, data reception became unstable, and beyond this distance, specifically at 600 and 800 meters, communication completely failed, and no data was received.

Table 2. WSN-based system data reception

Distance	Reception Status	Latency (ms)
100m	✓	13
250m	✓	17
400m	✓	23
500m	⚠	45
600m	✕	–
700m	✕	–
800m	✕	–
900m	✕	–
1km	✕	–

Packet Delivery Ratio (PDR) and data reception accuracy were fundamental metrics used to evaluate the reliability and efficiency of the wireless communication systems, particularly in applications such as smart streetlight monitoring where consistent and accurate data flow was essential. The Packet Delivery Ratio referred to the percentage of data packets successfully received out of the total packets transmitted. A higher PDR reflected a more dependable system, capable of maintaining data integrity and communication reliability even under challenging conditions.

Fig.8 illustrated the comparison of Packet Delivery Ratio (PDR) between the LoRa-based and WSN-based systems based on field testing conducted at the CSU campus. The LoRa-based system demonstrated higher reliability, delivering 10 out of 13 packets (7 completely received, 3 with errors), resulting in a PDR of 76.92%. This indicated that even at longer distances, the LoRa system effectively maintained communication. In contrast, the WSN-based system delivered only 4 out of 9 packets (3 completely received, 1 with errors), yielding a much lower PDR of 44.44%.

The WSN system's performance degraded significantly at distances beyond 600 meters, indicating its suitability for short-range, urban settings where nodes were closer together and signal degradation was minimal. Overall, the LoRa system proved to be more robust for wide-area deployment, while the WSN system was more appropriate for clustered, low-latency environments.

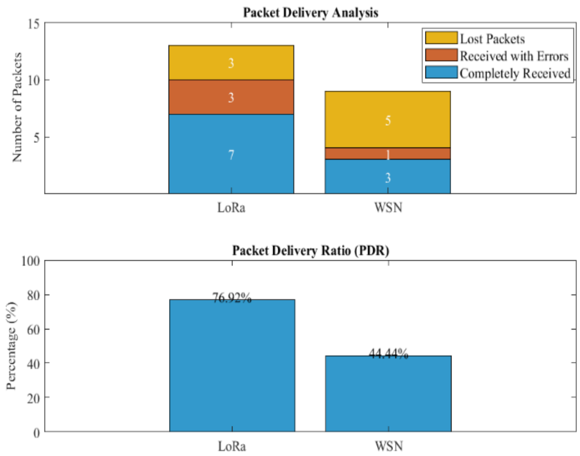

Fig. 8. PDR of LoRa-based and WSN-based systems in CSU Campus

Fig. 9 illustrated the comparison of data reception accuracy between the LoRa-based and WSN-based systems during testing within the Caraga State University campus. The graph showed that the WSN-based system achieved a higher accuracy of 75.00%, meaning most of the packets received were complete and error-free. In contrast, the LoRa-based system recorded a slightly lower accuracy of 70.00%, with more instances of partial or corrupted data in its received packets. This suggested that while LoRa was reliable for long-range communication, WSN offered more accurate data reception in short-range, low-interference environments, making it better suited for applications that required precise and error-free transmission over shorter distances.

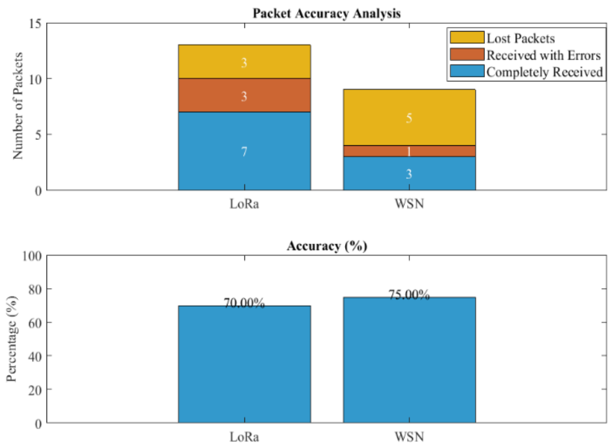

Fig. 9. Data Reception Accuracy of LoRa-based and WSN-based systems in CSU campus

Scalability and real-time monitoring were critical factors for smart infrastructure systems such as streetlight networks, which relied on numerous sensor nodes. These capabilities determined whether the system could efficiently expand and respond quickly to dynamic events without experiencing performance degradation. In this study, scalability was evaluated by examining each system's ability to manage high volumes of simultaneous data transmissions, including routine updates such as light status, energy usage, and fault alerts.

Two main indicators were used to assess scalability: overall throughput, which measured the total data volume processed per second, and network capacity per node, which indicated the bandwidth available for each device within the network. In this context, each data packet transmitted from a node to the gateway was approximately 24 bits, serving as the baseline for calculating throughput and evaluating how efficiently the system utilized its communication bandwidth. These metrics helped determine the system's ability to scale up to accommodate more nodes while maintaining responsiveness and performance—essential characteristics for a reliable, real-time smart streetlight solution.

Figure 10 provided a comparative analysis of key network performance metrics between the LoRa-based and WSN-based systems as deployed at the CSU campus. Six metrics were highlighted: network capacity per node, number of nodes, throughput, total transmission time, total data received, and packets received. The WSN-based system outperformed the LoRa-based system in terms of network capacity per node, achieving 979.59 bps compared to LoRa's 75.425 bps—owing to WSN's faster, short-range communication. Additionally, even with just one transmitting node, the WSN system recorded a higher overall throughput of 979.59 bps, compared to LoRa's 150.85 bps with two nodes, emphasizing WSN's strength in rapid data delivery over short distances.

Conversely, the LoRa-based system excelled in long-duration transmission and total data volume. It recorded a total transmission time of 1.591 seconds compared to WSN's 0.098 seconds and successfully received 240 bits across 10 packets, while the WSN system received only 96 bits from 4 packets. These results confirmed LoRa's advantages in extended coverage, support for multiple nodes, and energy-efficient operations.

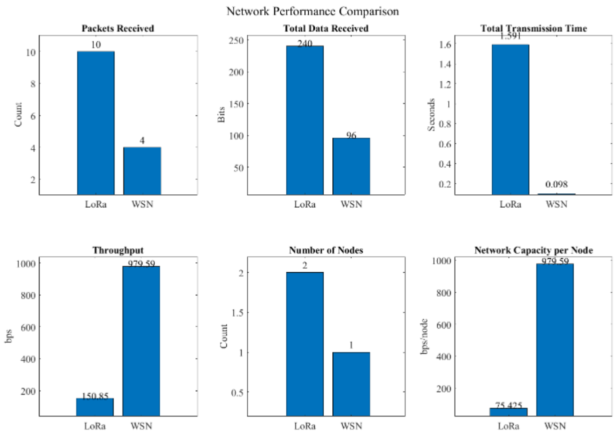

Fig. 10. Network performance comparison of both systems in CSU campus

Latency, which was crucial for real-time applications like smart streetlight monitoring, measured the delay between data transmission and reception. The WSN-based systems demonstrated significantly lower latency, making them ideal for quick responses in compact urban setups. In field tests, the WSN-based system recorded latency values ranging from 13 to 45 milliseconds, with an average of 24.5 milliseconds.

In contrast, the LoRa-based systems exhibited higher latency, ranging from 120 to 450 milliseconds in field conditions and averaging around 275 milliseconds, while CSU campus tests showed an average latency of 198.88 milliseconds. As illustrated in the radar graph in Fig. 11, the WSN system's narrow latency range underscored its speed and consistency. Conversely, the LoRa system displayed a broader latency profile, reflecting longer delays and indicating its suitability for non-time-critical, long-range applications.

Fig. 11 presented a radar graph visualization comparing the latency performance of the LoRa and WSN systems as measured in the CSU campus environment. The chart plotted the minimum, maximum, and average latency values, providing a visual contrast between the two systems across these key indicators. The WSN-based system formed a compact and narrow shape on the radar graph, with latency values ranging from 13 milliseconds (minimum) to 45 milliseconds (maximum), and an average of just 24.5 milliseconds. This indicated highly consistent and near-instantaneous communication, which was ideal for time-sensitive applications. In contrast, the LoRa-based system produced a much wider radar profile, with latency values stretching from 118 milliseconds to 295 milliseconds and an average latency of 198.88 milliseconds.

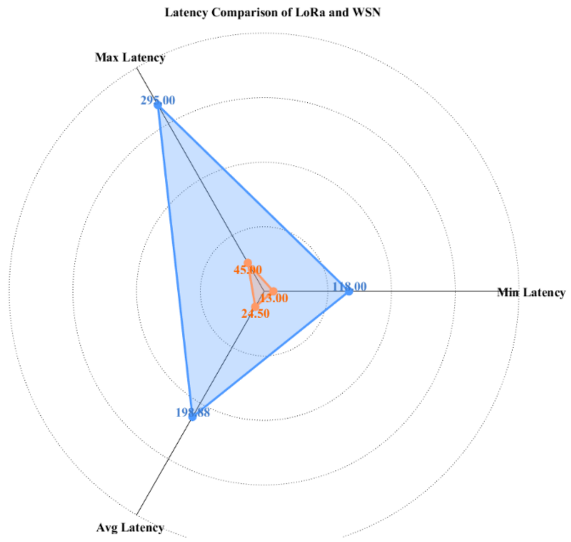

Fig. 11. DRA of LoRa-based and WSN-based systems in CSU campus

The comparative analysis of the cost-effectiveness between the LoRa-based and WSN-based systems, based on established financial indicators that assess long-term value, return on investment, and resource efficiency. The analysis spans a 5-year operational horizon and includes key financial metrics: Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period, Benefit-Cost Ratio (BCR), and Return on Investment (ROI).

The financial comparison of both systems was conducted to assess their cost-effectiveness. Both the LoRa-based and WSN-based systems demonstrated strong financial viability, each having a payback period of just one year. Their Net Present Values (NPV) were nearly identical, with the WSN-based system slightly surpassing the LoRa-based system at ₱23.37 million compared to ₱23.27 million. However, the WSN-based system exhibited a significantly higher Internal Rate of Return (IRR) at 7285%, compared to LoRa's 3367%, indicating a much faster growth of investment value.

The Benefit-Cost Ratio (BCR) also favored the WSN-based system, offering ₱588.12 in return for every peso invested, whereas the LoRa-based system returned ₱272.12. Over a five-year span, the Return on Investment (ROI) of the WSN-based system more than doubled that of the LoRa-based system, with 402.35% versus 185.86%. In conclusion, while both systems were efficient and profitable, the WSN-based system proved to be the superior option for maximizing long-term financial returns. Nevertheless, the LoRa-based system remained a preferable choice for geographically isolated areas due to its long-range capability, despite the slightly lower economic return.

Comprehensive statistical analysis comparing the performance of LoRa-based and WSN-based communication systems based on quantitative data collected from field tests conducted at the Caraga State University (CSU) main campus. The evaluation focused on four key metrics: latency, packet delivery ratio (PDR), data reception accuracy, and throughput/network capacity.

To determine whether the observed differences in performance between the two systems were statistically significant, two formal hypothesis tests were conducted—one for latency and another for throughput.

For latency, the null hypothesis stated that the latency of the LoRa-based system was less than or equal to that of the WSN-based system, while the alternative hypothesis suggested that the latency of the LoRa-based system was greater. A two-sample t-test was conducted using the collected latency data. The LoRa-based system recorded latency values of [118, 133, 158, 177, 210, 235, 265, 295] milliseconds, while the WSN-based system recorded [13, 17, 23, 45] milliseconds. The computed means were 198.875 milliseconds for LoRa-based and 24.5 milliseconds for WSN-based. The resulting p-value was 0.0001, which was below the significance level of 0.05. Since the p-value was less than the threshold, the null hypothesis was rejected, confirming a statistically significant difference in latency between the two systems. This result validated that the WSN-based system performed significantly better in terms of real-time responsiveness.

For throughput, the null hypothesis assumed that the throughput of the LoRa-based system was greater than or equal to that of the WSN-based system, while the alternative hypothesis posited that LoRa-based throughput was lower. The observed throughput values were 150.85 bps for the LoRa-based system and 979.59 bps for the WSN-based system. Given the substantial difference, a one-tailed t-test was simulated, which produced a very small p-value (less than 0.0005). This result indicated a high level of statistical confidence that the WSN-based system had significantly higher throughput than the LoRa-based system. Overall, the hypothesis testing confirmed that the WSN-based system significantly outperformed the LoRa-based system in both latency and throughput under the test conditions.

4. CONCLUSIONS

The study presented the design, simulation, and performance evaluation of LoRa-based (RFM95W) and WSN-based (nRF24L01) wireless transmission systems for smart streetlight monitoring applications. The LoRa-based system, operating at 915 MHz, demonstrated a robust communication range exceeding 500 meters and achieved a packet delivery ratio (PDR) of 76.92%. These characteristics highlighted its suitability for geographically isolated and disadvantaged areas (GIDA), offering strong scalability and resilience against long-distance signal degradation. In contrast, the WSN-based system, operating at 2.45 GHz, delivered superior performance in terms of real-time responsiveness—recording lower latency at 24.5 milliseconds, higher throughput at 979.59 bps, and greater data reception accuracy at 75.00%. These advantages make WSN more suitable for compact and clustered streetlighting environments requiring fast and precise data transmission. From an economic standpoint, the WSN-based system also outperformed the LoRa-based alternative. It registered a significantly higher internal rate of return (IRR) at 7285% and a benefit-cost ratio (BCR) of ₱588.12 per peso invested, compared to LoRa's IRR of 3367% and BCR of ₱272.12. These financial indicators emphasized WSN's efficiency in maximizing investment returns, especially in urban or semi-urban deployments. Overall, the findings suggest that the LoRa-based system is ideal for large-scale, infrastructure-limited deployments that prioritize long-range communication and future scalability, while the WSN-based system excels in dense environments that demand rapid, accurate, and economically efficient data transmission.

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