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Low-Power Communication Algorithm for Optimized Energy Consumption in Wireless Sensor Network-Based Solar Streetlights Technology

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Abstract: *This study presents the design and development of a low-power communication algorithm for optimizing energy consumption in wireless sensor networks (WSNs) deployed in solar-powered streetlights. The system utilizes ESP32 microcontrollers integrated with INA219 sensors and LoRa modules to measure and transmit data from streetlights. A dynamic clustering algorithm elects the node with the highest battery voltage as the cluster head (CH) to aggregate and forward data from other nodes to a central receiver, while the non-cluster head nodes enter deep sleep mode after transmission, reducing redundant communications and conserving energy. The performance of the clustering-based transmission was compared against direct transmission in terms of energy consumption during data exchange. Results demonstrate a 49.45% reduction in energy consumption using the clustering approach compared to direct transmission, confirming its effectiveness for extending the operational lifespan of WSN nodes in energy-constrained environments. This solution offers an energy-efficient communication strategy for smart streetlight systems.*

Keywords: Wireless Sensor Networks, Energy Consumption Reduction, Clustering, Deep Sleep, LoRa Communication

1. INTRODUCTION

Street lighting is a fundamental component of public infrastructure that contributes to safety, security, and mobility in both urban and rural environments [1].
Conventional streetlight systems are commonly powered through centralized electrical grids. In many developing regions, such as the Philippines, this can be particularly challenging. Certain areas still experience limited access to reliable electricity, which hinders the consistent operation of traditional lighting systems [2].
In response to these challenges, solar-powered streetlights have emerged as a sustainable alternative because they operate independently of the grid. Solar streetlights are ideal for remote areas, disaster-prone locations, and communities seeking to reduce their energy costs and carbon footprint [3].
However, despite their advantages, solar streetlight systems are not without limitations. Their performance may degrade over time due to factors such as battery aging, solar panel inefficiency, and environmental conditions. In many cases, faults go unnoticed until users report outages, which can lead to delays in maintenance and reduce public confidence in the system [4].
As such, monitoring the status and performance of these systems is essential to ensure their reliability and longevity [4]. Integrating monitoring capabilities like Wireless Sensor Networks (WSNs) and IoTs allows real-time tracking of various parameters, including energy consumption, battery health, and solar charging efficiency[5][6]. These systems play a critical role in preventive maintenance, fault detection, and energy optimization [7].
A major challenge in the deployment of WSNs, especially in solar-powered systems, is power consumption. In solar streetlight WSNs, sensor nodes are powered by limited solar energy, making efficient energy use critical to ensuring the system's long-term functionality. Studies have shown that more than 50% of the energy consumed by WSN nodes is spent on communication, including data transmission and reception [8]. Factors such as transmission distance, frequent data exchanges, and the energy demands of sensing and processing can significantly deplete energy reserves, reducing the system's overall reliability. The high communication energy expenditure reduces the operational lifespan of solar streetlight WSNs and may compromise their ability to perform real-time monitoring effectively. Given the limited energy available from solar power, optimizing power consumption in communication is critical to maintaining the system's reliability and performance. There is a need to identify and implement a low-power communication algorithm that can reduce energy consumption without compromising data integrity or communication range, ensuring that solar streetlights can operate efficiently over extended periods [9].
The main objective of this study is to optimize low-power communication protocols using techniques from different studies to improve data transmission efficiency and lessen the power consumption of wireless sensor networks in remote monitoring systems. The specific objectives are:

- To design and implement an energy consumption optimization system, achieving a targeted 10-20% reduction in energy consumption in the communication process using clustering and deep sleep techniques for solar-powered streetlights
- To evaluate and validate the developed system.

This study is significant in addressing one of the key limitations in the implementation of solar-powered Wireless Sensor Networks (WSNs) for streetlight systems: inefficient energy consumption due to communication overhead. By designing a low-power communication algorithm that incorporates energy-saving techniques such as clustering, idle listening avoidance, and deep sleep scheduling, helps in enhancing the energy efficiency in data transmission, improve monitoring, and reliability in transmitted data packets assisting local governments and utility managers in making informed, data-driven decisions for the maintenance of solar streetlight networks [10].

The study is limited in the following ways:

- The design and optimization of the device will focus on theoretical and laboratory-based assessments.
- The study will not cover aspects of hardware development beyond optimizing the communication algorithm for reducing energy consumption.

Despite these limitations, the study aims to contribute valuable insights into energy-efficient communication in WSNs and provide a foundation for future research and practical applications.

2. REVIEW OF RELATED LITERATURE

This chapter presents a review of previous studies and literature related to low-power communication, energy-efficient algorithms, wireless sensor networks (WSNs), and solar-powered streetlighting systems. The discussion emphasizes the integration of these technologies to enhance energy optimization and system performance.

2.1 Energy consumption in WSNs

Wireless Sensor Networks (WSNs) are a cornerstone of modern intelligent systems, enabling remote sensing, data gathering, and communication in a decentralized manner.

A WSN node typically consumes energy in three primary domains: sensing, data processing, and communication. Among these, communication, especially wireless transmission and reception, is the most energy intensive [11]. Heinzelman W. R., (2000) demonstrated that the energy consumed during data transmission can be magnitudes higher than the energy required for data processing [12].

As most WSN nodes are battery powered, their lifetime is highly dependent on their energy consumption. Communicating energy is the major contributor to the total energy expenditure and is determined by the total amount of communication and the transmission distance [13].

The study about a review on energy efficient protocols in wireless sensor networks conducted by Yadav R. N., (2015) showed that more than 50 % of energy is spent during communication activity by a sensor node as shown in Fig 1. The energy cost of transmitting a single bit of information is approximately the same as that needed for processing a thousand operations in a typical sensor node [14].

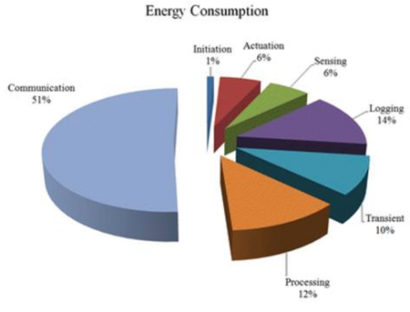

Fig. 1. Allocation of energy consumption in WSN

2.2 Routing protocols in WSN

Optimization algorithms play a critical role in enhancing the efficiency, reliability, and lifespan of Wireless Sensor Networks (WSNs) [7]. These algorithms are used to solve complex problems involving resource allocation, routing, scheduling, clustering, and power management, each of which can significantly influence the overall performance and sustainability of the network.

2.2.1 Clustering in transmission

In direct transmission, where each sensor node sends data directly to the base station, can lead to rapid energy depletion, especially for nodes that are farther away. Similarly, multi-hop routing can overburden certain nodes, leading to uneven energy distribution and potential network failures.

To address these challenges, the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol was developed. LEACH introduces a clustering-based approach that significantly enhances energy efficiency by rotating the role of cluster heads (local base stations) among the nodes. This randomized rotation ensures that the energy load is evenly distributed, preventing any single node from being overused.

Simulation studies of Behera et al., (2022) showed that LEACH's ability to distribute energy consumption evenly across the network effectively doubles the network's operational lifespan, making it a robust solution for extending the longevity of WSNs in various applications [15].

2.2.2 Duty cycle and scheduling optimization

Duty cycling is a widely adopted technique to reduce energy consumption, where nodes alternate between active and sleep states. By minimizing the duration that a node remains awake and idle, significant power can be conserved.

The study by Amengu et al. (2022) highlighted the strength of SMAC as an asynchronous duty cycle MAC protocol suitable for monitoring applications where sensor nodes do not need to transmit data regularly, such as in streetlight monitoring [16]. The study emphasized that SMAC uses energy-saving methods to address energy dissipation in sensor nodes by targeting issues such as idle listening, packet overhearing, control overhead, and packet collisions.

2.2.3 Data dissemination

Data dissemination refers to the process of routing data within sensor networks, where new nodes are identified to handle specific events. However, nodes with low energy levels can hinder the information transmission process across the network. To address this issue, the data dissemination process prioritizes the selection of optimized nodes for broadcasting information.

The study by Behera et al., (2022) highlighted the importance of the Energy-Efficient Data Dissemination (EEDD) routing protocol in optimizing cluster head (CH) selection within the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol. In LEACH, cluster heads are randomly selected, which increases the likelihood of nodes with low residual energy becoming cluster heads. This can lead to rapid energy depletion, leaving these nodes unable to perform critical functions, such as sensing and communication. EEDD addresses this challenge by incorporating multiple parameters into the cluster head selection process, including the initial energy of nodes, the average network energy, energy consumption rates, and residual energy. These factors ensure that nodes are continuously monitored, and the cluster head is chosen based on the node with the highest energy value [15].

2.3 Gaps in existing literature

LEACH (Bahera et al., 2022) has been widely recognized for its ability to reduce power consumption and support scalability; however, it lacks mechanisms to minimize idle listening and optimize cluster formation dynamically. Its random cluster head election process may repeatedly select the same node, causing it to drain energy faster and ultimately preventing it from handling further transmissions [15]. Additionally, it has not been validated through hardware implementation.

S-MAC, on the other hand, effectively reduces both power consumption and idle listening through periodic sleep schedules but does not support optimized clustering or scalability, nor has it been implemented in hardware [14].

EEDD (Anil et al., 2020) addresses the need for efficient cluster formation and scalability, yet it overlooks idle listening and lacks real-world hardware testing [17].

In contrast, the proposed study integrates all features. It reduces power consumption and idle listening through dynamic cluster head election and the use of deep sleep in non-cluster head nodes. It also optimizes cluster formation based on real-time battery voltage, demonstrates scalability, and has been successfully implemented on an actual hardware setup.

Table 1. Gaps in Literature

Routing Protocols	Reduce Energy Consumption	Reduce Idle Listening	Optimize Cluster Formation	Hardware
LEACH (Bahera et al, 2022)	✓	x	x	x
S-MAC (Amengu et al, 2022)	✓	✓	x	x
EEDD (Anil et al, 2020)	✓	x	✓	x
Proposed Study	✓	✓	✓	✓

3. METHODS

This chapter of the study focuses on the procedures and processes undertaken in the study. It covers the integration of different optimization techniques such as clustering and deep sleep, the design and implementation of the device or the system, as well as the hardware components used. It also discusses the data gathering procedure and testing.

3.1 System overview

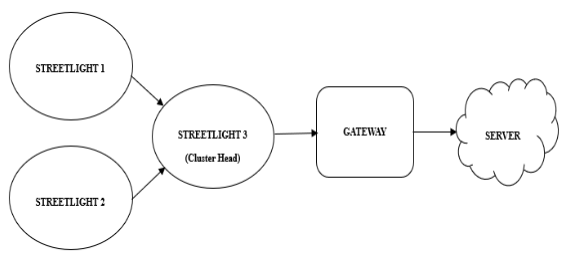

Fig. 2. System design

In this system, Streetlight 1, Streetlight 2, and Streetlight 3 are represented by Transmitter 1, Transmitter 2, and Transmitter 3, respectively. Each streetlight independently generates and transmits sensor data, including bulb voltage and current, solar panel state of charge, solar voltage and current, and battery output voltage and current. The system implements a clustering mechanism inspired by the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol. Among the transmitters, one node is selected as the Cluster Head (CH) illustrated by Streetlight 3 in Fig 2. The CH aggregates sensor data from the non-cluster head nodes (Streetlight 1 and Streetlight 2) and transmits the combined dataset to a central receiver or gateway.

3.1.1 Conceptual framework

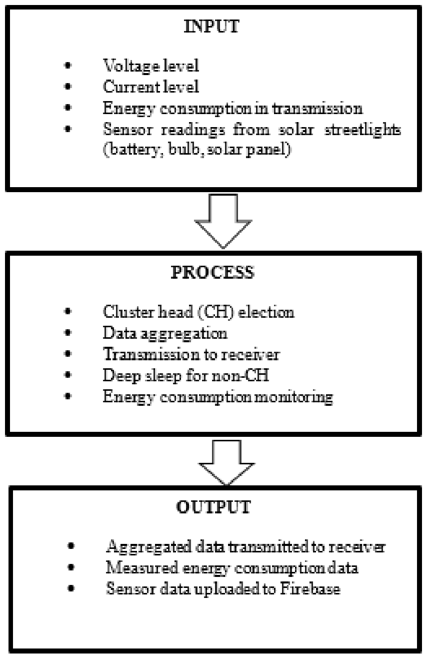

Fig. 3. Conceptual framework of the system

3.1.2 System Flow

The operational flow of the system is illustrated in fig.4. At 1-minute intervals, each streetlight collects sensor data, including bulb voltage and current, solar panel voltage and current, the panel's state of charge, and battery output voltage and current. After data collection, all streetlights broadcast their respective state of charge and listen for broadcasts from the others. Once all values have been shared, the streetlight with the highest state of charge is elected as the Cluster Head (CH).

The non-cluster head nodes transmit their sensor data to the CH and then enter deep sleep mode to conserve energy. The CH aggregates its data along with that received from the other nodes and forwards the complete dataset to the receiver. The receiver collects the transmitted data and uploads it to a server or Firebase.

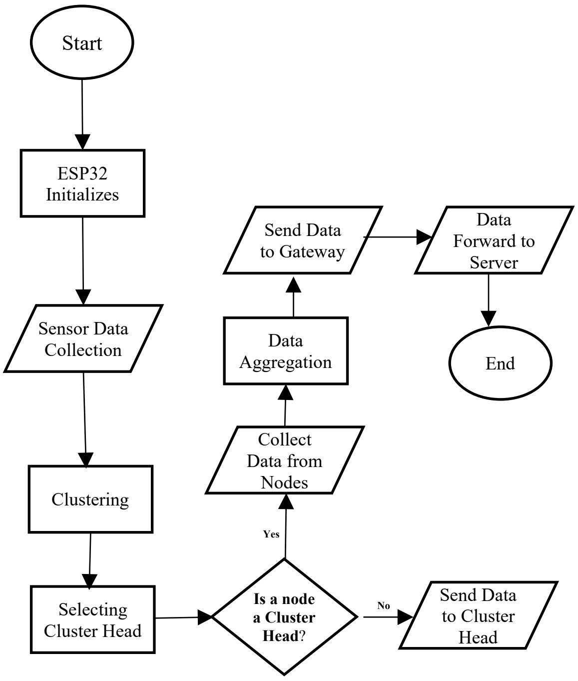

Fig. 4. Flowchart of the system

3.1.3 Connection

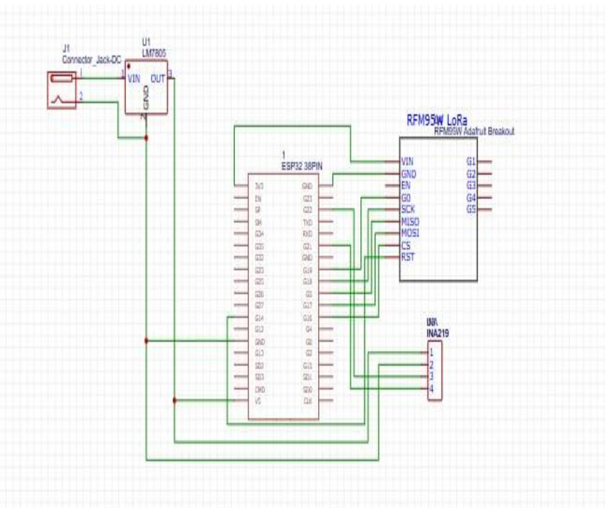

Fig. 5. Schematic Diagram

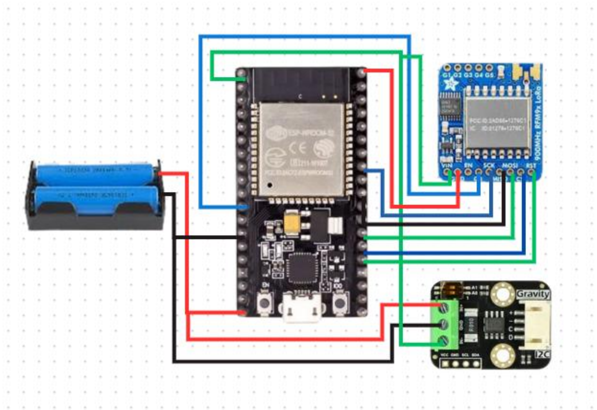

Fig. 6. Connection of the components

The system prototype was built using hardware components such as a battery, ESP32 microcontroller, an Adafruit RFM95W LoRa module, and a DFRobot INA219 current sensor that enable wireless communication, energy monitoring, and efficient power management. Each component was selected based on its compatibility, power efficiency, and ability to meet the technical requirements of the project.

3.1.4 System prototype

The hardware system was designed to support efficient data acquisition, wireless communication, and energy monitoring for a WSN-based application.

Fig. 7. System prototype

4. RESULTS

The energy consumed during transmission and reception was measured through the data gathered from the series of transmissions conducted.

```
--- New Round ---
-> Voltage: 4.992 V
-> Phase 1: Listening...
-> Received from TRANSMITTER3: 4.676 V
-> Received from TRANSMITTER2: 4.972 V
-> Phase 2: Broadcasting voltage...
-> Broadcasted voltage: 4.992 V
-> Phase 3: Listening again for higher votes...
-> Elected CH: TRANSMITTER1 (4.992 V)
-> I am the Cluster Head
-> CH sent final aggregated data to receiver.
```

Fig. 8. Cluster head election

The displayed output represents the Cluster Head (CH) selection process in a LEACH-based wireless sensor network, where nodes dynamically elect a CH based on their current battery voltage. This process ensures that the node with the most remaining energy assumes the role of cluster head, promoting energy efficiency and extending the operational lifespan of the network.

```
=== TRANSMITTER1 ONLINE ===

--- New Round ---
-> Broadcasted voltage: 5.348 V
-> Received TRANSMITTER3: 5.396 V
-> Received TRANSMITTER2: 5.105 V
-> Elected CH: TRANSMITTER3 (5.396 V)

========= TRANSMITTED DATA =========
Node:       TRANSMITTER1
Time:       2025-04-25_02-58-13
Bulb:       13.44 V, 0.13 A
Solar:      10.72 V, 1.95 A
Battery:    5.35 V, 0.94 A
SoC:        73 %
Energy:     0.0070 mWh
====================================
-> Data sent to CH, going to deep sleep 55s
```

Fig. 9. Transmitter 1 as a non-CH node

The figure shows the behavior of transmitter 1 when it is not elected as the Cluster Head (CH) during a round of communication in a LEACH-based wireless sensor network. At the start of the new round,
transmitter 1 broadcasts its battery voltage, then receives voltage readings from transmitter 3 and transmitter 2.
As a non-CH node, transmitter 1 proceeds to gather and transmit its sensor data. After transmitting this data to the elected CH transmitter 3, transmitter 1 enters deep sleep mode for to conserve energy, which is a core principle of energy-efficient operation in clustered wireless sensor networks. This behavior reflects the correct implementation of the LEACH protocol, ensuring that only the CH remains active for data aggregation and transmission to the base station.

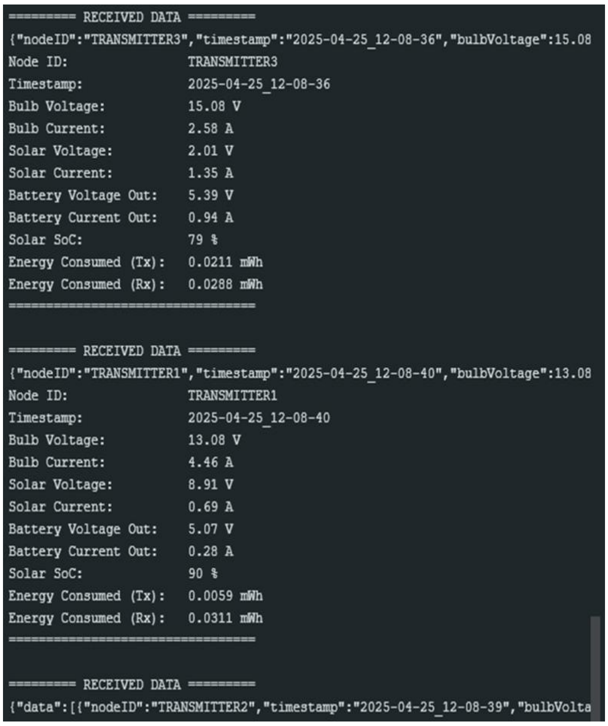

Fig. 10. Data packet received

The figure above illustrates three data packets that were successfully received by the receiver module from the cluster head transmitter in the wireless sensor network. Each data packet includes a structured set of information, including a timestamp and several sensor readings.
The sensor readings in each packet represent real-time measurements gathered by the corresponding transmitter node.

Fig. 11. Transmitter 1 node in Firebase

Firebase acts as a wireless cloud-based database for collecting, storing, and viewing sensor data from the transmitters and receivers in real time. The data packets received by the receiver from the transmitters are uploaded to Firebase for real-time monitoring and secure storage.

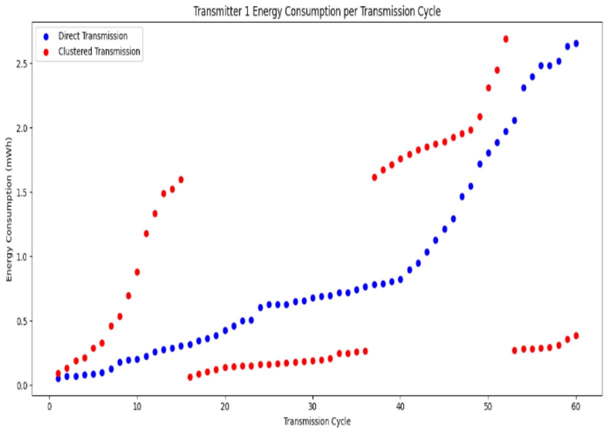

Fig. 12. Transmitter 1 energy consumption

The graph shows the energy consumption of direct and clustered transmission methods for Transmitter 1 over 60 minutes. The direct transmission, represented by the solid blue line, exhibits a steady upward trend, as the transmitter remains continuously active throughout the duration, constantly listening for and communicating with the receiver.
In contrast, the clustered transmission, shown by the dashed red line, displays periods of increased energy consumption, particularly when the transmitter is elected as the cluster head. During these times, it aggregates data packets from the non-cluster head nodes and transmits the combined payload to the receiver. The sudden spikes in energy consumption are due to the larger payload size the cluster head needs to send, requiring more power compared to regular transmissions. The drop in energy consumption signifies that Transmitter 1 was no longer acting as the cluster head and transitioned into sleep mode to conserve energy.

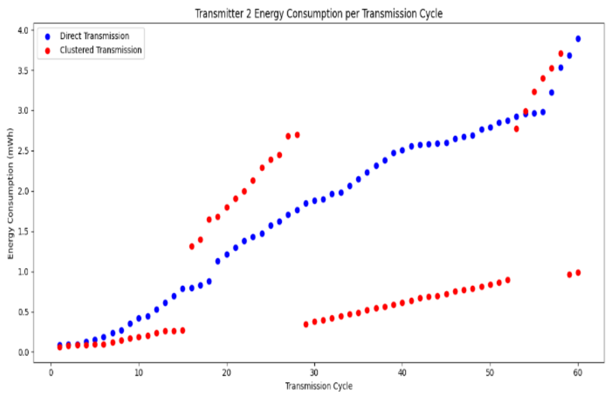

Fig. 13. Transmitter 2 energy consumption

The graph shows a comparison between the energy consumption of direct and clustered transmission methods for Transmitter 2.
The direct transmission exhibits a steady and continuous rise in energy consumption. This consistent increase reflects the transmitter's ongoing activity, continuously sending data directly to the receiver without any breaks

or power-saving mechanisms, which leads to higher energy use over time.

In contrast, the clustered transmission follows a less consistent pattern. For most of the duration, energy consumption remains relatively low and flat. However, noticeable spikes are indicating the periods when Transmitter 2 was selected as the cluster head (CH). As CH, it aggregates data from other nodes and transmits the combined payload to the receiver, requiring more energy. Outside these active periods, the transmitter consumes very little energy, suggesting it stays in a low-power sleep mode, conserving power.

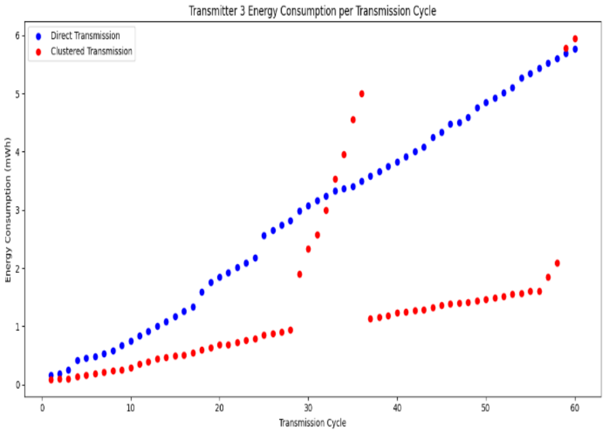

Fig. 14. Transmitter 3 energy consumption

The graph shows the energy consumption of two different communication strategies, direct transmission and clustered transmission. With direct, the energy consumption steadily rises throughout the entire hour, reflecting constant activity as the transmitter continuously sends data to the receiver.

In contrast, the clustered transmission paints a very different picture. For most of the 60-minute duration, energy consumption stays very low. However, there are noticeable sharp spikes, where energy briefly rises before quickly dropping again. These spikes likely happen when Transmitter 3 takes on the role of Cluster Head, meaning it collect and forward data, leading to short bursts of higher energy use. The rest of the time, the transmitter sends data packets to a cluster head and enters a low-power sleep mode, conserving energy.

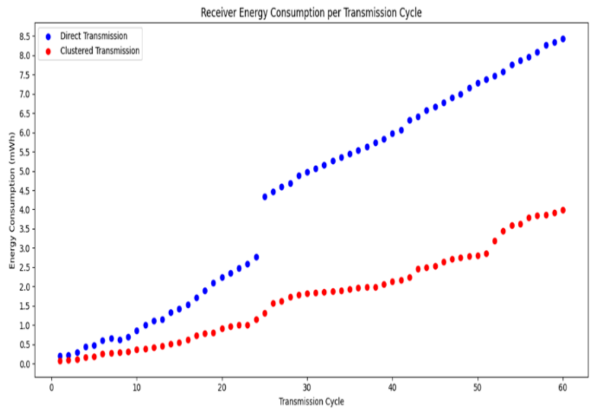

Fig. 15. Energy consumption in receiver.

The graph above compares the energy consumption of the receiver in direct and clustered transmission. In direct transmission, the energy consumption rises steadily throughout the experiment since it receives data packets from three transmitters in a minute. By the end of the 60 minutes, the receiver consumes approximately 8.4 mWh under direct transmission.

On the other hand, the clustered transmission exhibits a much more gradual and consistent increase in energy consumption, yet receiver's energy usage remains much lower. By the end of the experiment, clustered transmission has consumed just around 4.0 mWh, which is about half of what was consumed during direct transmission. This difference clearly highlights the energy-saving benefits of clustering. Since nodes send their data to a cluster head for aggregation before sending a single transmission to the receiver, the frequency and volume of direct communication are significantly reduced. As a result, the receiver experiences less radio activity and processing load, saving energy.

Table 2. Energy Consumption of the System

	Energy Consumption	
	Direct	Clustered
Transmitter 1	54.31 mWh	48.45 mWh
Transmitter 2	106.31 mWh	65.25 mWh
Transmitter 3	174.57 mWh	83.57 mWh
Receiver	260.03 mWh	103.62 mWh

Table 2 shows the energy consumption for both direct and clustered modes across the transmitter and receiver components of the system.

In direct mode, each transmitter and the receiver consume more energy as they are continuously transmitting or receiving data without any energy-saving measures. For example, Transmitter 1 consumes 54.31 mWh, Transmitter 2 consumes 106.31 mWh, Transmitter 3 uses 174.57 mWh, and the receiver consumes 260.03 mWh.

In clustered mode, the energy consumption decreases significantly because the system optimizes data transmission. Only the cluster head (which could be any of the transmitters based on energy levels) sends data to the receiver, reducing the energy consumption for the other non-cluster head transmitters, which enter low-power sleep modes. As a result, Transmitter 1's energy usage drops to 48.45 mWh, Transmitter 2's to 65.25 mWh, Transmitter 3's to 83.57 mWh, and the receiver consumes 103.62 mW.

The energy consumption reduction is calculated using the formula:

$$E_{reduction} = \frac{E_{direct} - E_{clustered}}{E_{direct}} \times 100 \qquad (1)$$

Where:

$E_{reduction}$ = Percentage of energy reduction (%)

E_{direct} = Total energy consumed in direct transmission mode

$E_{clustered}$ = Total energy consumed in clustered transmission mode

In this case, the total energy consumed in direct mode is 595.22 mWh, while in clustered mode, the energy consumption drops to 300.90 mWh. Substituting these values into the formula:

$$E_{reduction} = \frac{595.22 - 300.90}{595.22} \times 100$$

$$E_{reduction} = 49.45\ \%$$

5. CONCLUSION AND RECOMMENDATION

This part of the study includes the conclusion and recommendations of the researchers with regard to the current study. Conclusions and recommendations made were based on the results of the experiments conducted.

5.1 Conclusion

The comparison between direct and clustered transmission methods across Transmitters 1, 2, 3, and the receiver demonstrated that clustered transmission significantly reduces energy consumption.

In direct transmission, all devices showed a steady and continuous rise in energy usage, reflecting the constant activity required to directly communicate with the receiver. In contrast, clustered transmission introduced a more energy-efficient behavior, transmitters only consumed higher energy when acting as cluster heads, while otherwise maintaining very low energy usage through sleep modes.

The results are especially notable for the receiver, where clustered transmission nearly halved the energy consumption compared to direct transmission. This reduction in radio activity and processing load highlights the advantage of using clustering in wireless sensor networks (WSNs).

Overall, the findings confirm that 49.45 % of energy is reduced in applying clustering and deep sleep scheduling compared to direct transmission. It signifies that implementing clustered transmission is an effective strategy for prolonging the operational lifetime of WSN-based solar streetlights. By minimizing redundant transmissions and enabling low-power operation when not serving as cluster heads, clustering significantly optimizes energy efficiency across the network.

5.2 Recommendation

For future research, the researchers recommend using simulation tools to model larger networks and different conditions. Simulations can help predict how the system would perform with more devices, at greater distances, or in more complex environments.

It is also highly encouraged to implement the developed system in real solar streetlight applications. Deploying the setup in an actual environment would provide deeper insights into how well the system performs over time, under real weather and usage conditions. Combining both simulation and real-world deployment would give future studies a stronger, more complete understanding of how the technology works and how it can be improved.

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