Enhancing Precision Agriculture Efficiency through Edge Computing-Enabled Wireless Sensor Networks: A Data Aggregation Perspective

MD Jiabul Hoque[1, 2], Md. Saiful Islam[2,*], Istiaque Ahmed[1] and Md. Nurullah[1]

[1]Department of Computer and Communication Engineering, International Islamic University Chittagong (IIUC), Chattogram 4318, Bangladesh;
2 Department of Electronics and Telecommunication Engineering, Chittagong University of Engineering & Technology (CUET), Chattogram 4349, Bangladesh; Correspondence: saiful05eee@cuet.ac.bd;
Presented at the 11th International Electronic Conference on Sensors and Applications (ECSA-11), 26–28 November 2024;

Abstract

Precision agriculture (PA), leveraging wireless sensor networks (WSN) for efficient data collection, is set to revolutionize intelligent farming. However, challenges such as energy efficiency, data collection time, data quality, redundant data transmission, latency, and limited WSN lifespan persist. We propose a novel edge computing-driven WSN framework (ECDWF) for PA, designed to enhance network longevity by optimizing data transmission to the base station (BS) and enhancing energy dissipation by abolishing data redundancy through aggregation. This framework involves a two-step data aggregation process: within clusters, where the cluster head (CH) aggregates data, and at a central network point, where an edge computing-enabled gateway node (GN) performs further aggregation. Our MATLAB simulation evaluates the proposed ECDWF against the Low-energy adaptive clustering hierarchy (LEACH) protocol and two classic sensing strategies, Effective Node Sensing (ENS) and Periodically Sensing with All Nodes (PSAN). Results reveal significant energy efficiency, quality of data (QoD) transmission, and network lifespan improvements. Due to reduced long-range transmissions, nodes in our scheme dissipate energy over 2500 rounds, compared to 1000 rounds in LEACH. Our method sends Data packets to the CH and Base Station (BS) for 2500 rounds at 3.6×10^{10} bits, while LEACH stops at 1000 rounds at 2×10^{10} bits data transmission rate. Our approach improves network stability and lifetime, with the first node dying at 2070 rounds versus 999 rounds in LEACH and the last node remaining functional until 2476 rounds compared to 1000 rounds in LEACH. Our proposed system, ECDWF, outperforms PSAN and ENS in latency, data collection time (DCT), and energy usage. At 50 Mbps, the communication latency of ECDWF is just 8 seconds, compared to 24 seconds for ENS and 45 seconds for PSAN. ECDWF maintains a QoD of 100% across various valid sensor and node counts, surpassing ENS and PSAN. Our contribution integrates edge computing with WSN for PA, enhancing energy utilization and data aggregation. This approach effectively tackles data redundancy, transmission efficiency, and network longevity, providing a robust solution for precision agriculture.

Introduction

Precision agriculture (PA) has emerged as a transformative approach to enhancing food production, with data collection and processing forming its foundation. Wireless Sensor Networks (WSNs) play a pivotal role in PA by monitoring critical environmental factors such as temperature, air quality, water conditions, and soil composition. However, WSNs face significant challenges due to their energy-intensive nature, with data transmission alone accounting for approximately 70% of their total energy consumption. Clustering techniques, where sensor nodes collect and aggregate data through cluster heads (CHs) before sending it to the base station (BS), help reduce redundancy and improve efficiency but still lead to gradual energy depletion and reduced network lifespan.

Two primary data-gathering methods used in WSNs are PSAN (Periodic Sensing and Aggregation Network), where all nodes collect data regularly, and ENS (Event-driven Node Selection), where only task-relevant nodes are activated for data collection. Modern WSNs encounter further challenges, including limited computational power, bandwidth, energy, and storage capacities, which create a delicate balance between resource limitations and the need for efficient multi-task management. These challenges often result in increased energy consumption, longer data collection times, invalid data, higher latency, and compromised Quality of Data (QoD).

While WSN research has extensively explored individual aspects of network architecture and efficiency, integrating critical metrics such as data collection time (DCT), QoD, energy efficiency, latency, and network lifetime remains underexplored. This lack of focus often causes agricultural WSNs and IoT systems to spend excessive time processing raw data, affecting their overall efficiency.

To address these challenges, a novel edge-computing-enabled WSN framework is proposed for intelligent agriculture. This approach introduces dual-level data aggregation: one at the CHs within clusters and another at the gateway node (GN), leveraging edge computing capabilities. By consolidating data at these aggregation points and reducing the number of transmissions to the BS, this strategy optimizes power consumption, enhances QoD, minimizes latency, and extends the network's operational lifespan. This innovative method aligns with the increasing complexity of modern agricultural applications and supports more efficient resource utilization in PA systems. This approach aims to enhance network lifetime and resource utilization in agricultural IoT systems.

The key contributions of this work are as follows:

1. We developed a framework for edge computing-enabled WSNs considering QoD and DCT constraints.
2. We proposed an edge computing-enabled technique for collecting valid data based on parameters such as node position and data type, ensuring high QoD with real-time execution.
3. We introduced a dual-level data aggregation approach, utilizing CHs and GNs to minimize data redundancy and reduce transmission frequency. This approach optimizes energy efficiency and extends network lifetime by consolidating data into a single long-range transmission from the GN to BS.

Methodology

The proposed edge computing-enabled WSN framework consists of three layers: the WSN layer, the edge computing layer, and the application layer. Data collection begins with task allocation to either edge servers or WSN nodes based on user requirements. In the first phase, clusters are formed, and cluster heads (CHs) are selected through a round-based process. Initially, CHs are chosen randomly, but in subsequent rounds, selection is determined by comparing nodes' energy levels to a threshold value. Once selected, CHs broadcast their status and invite nearby nodes to join their cluster, forming associations based on received signal strength. In the second phase, sensor nodes (SNs) transmit data to the CHs using a TDMA technique to prevent data collisions. CHs then aggregate the collected data and forward it to the gateway node (GN), where a second aggregation occurs using edge computing to eliminate redundancies and discard irrelevant data. This dual-level aggregation significantly reduces the amount of data transmitted to the base station (BS) and improves energy efficiency. Finally, the processed data is sent from the BS to the cloud server for further application and storage. This methodology enhances network performance, reduces redundancy, and extends network lifetime.

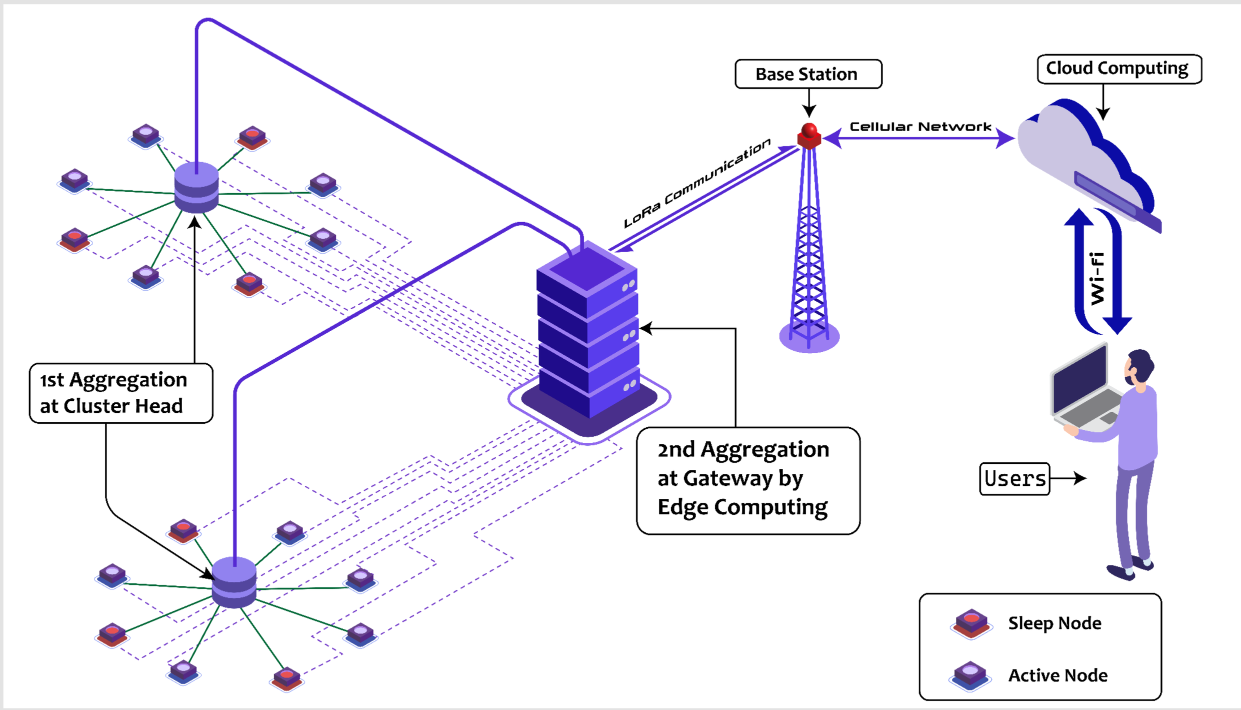
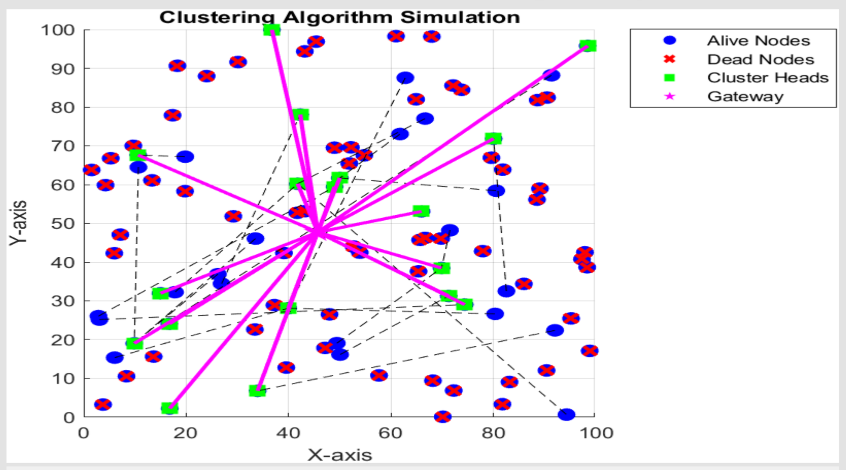


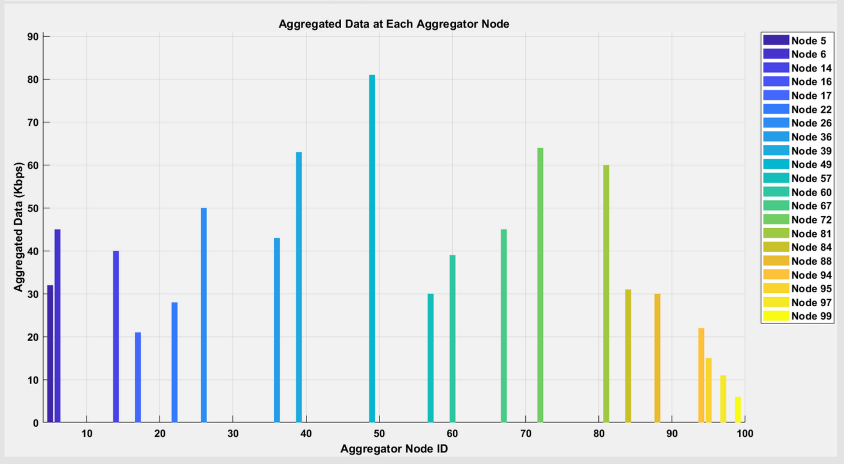
Fig. 1. Proposed Edge computing enabled WSN framework.

Results

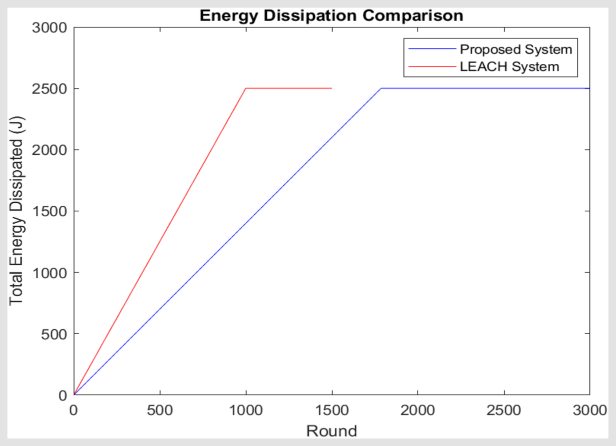
The proposed system involves nodes randomly distributed across a 100x100 farming area, where nodes with energy below a threshold are marked as dead. Connections between non-aggregating nodes and cluster heads (CHs) are shown with dashed lines, and solid lines represent links from CHs to the gateway (GN), simulating data forwarding. Nodes with sufficient energy are considered alive, and some are selected as candidate aggregators based on a probability threshold. One aggregator is chosen per sub-region to gather data from nearby nodes. Aggregated data from CHs is then transmitted to the GN. Figure 3 highlights the total aggregated data (in Kbps) received at the GN.

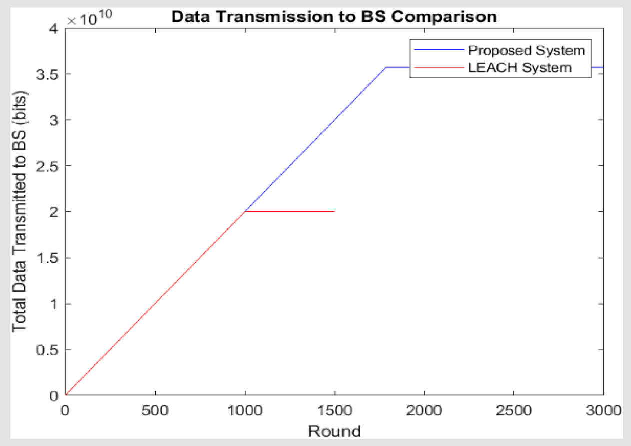
Our MATLAB simulation evaluates the proposed approach against the Low-energy adaptive clustering hierarchy (LEACH) protocol and two classic sensing strategies, Periodically Sensing with All Nodes (PSAN) and Effective Node Sensing (ESN). Results reveal significant energy efficiency, quality of data (QoD) transmission, and network lifespan improvements. Due to reduced long-range transmissions, nodes in our scheme dissipate energy over 2500 rounds, compared to 1000 rounds in LEACH. Our method sends Data packets to the CH and Base Station (BS) for 2500 rounds at 3.6x1010 bits, while LEACH stops at 1000 rounds at 2x1010 bits data transmission rate. Our approach improves network stability and lifetime, with the first node dying at 2070 rounds versus 999 rounds in LEACH and the last node remaining functional until 2476 rounds compared to 1000 rounds in LEACH. Our proposed system, ECDWF, outperforms PSAN and ENS in latency, data collection time (DCT), and energy usage. At 50 Mbps, the communication latency of ECDWF is just 8 seconds, compared to 24 seconds for ENS and 45 seconds for PSAN. ECDWF maintains a QoD of 100% across various valid sensor and node counts, surpassing ENS and PSAN.

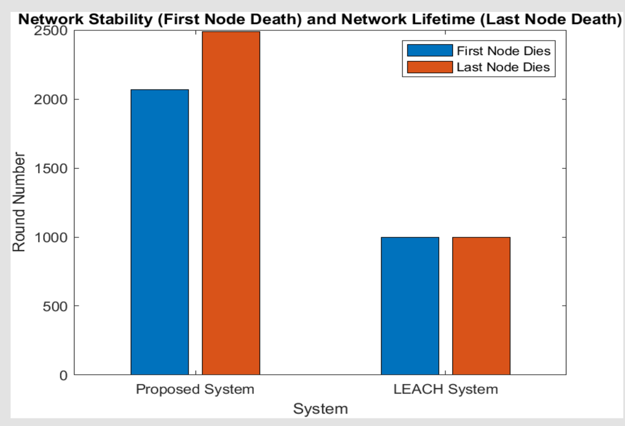


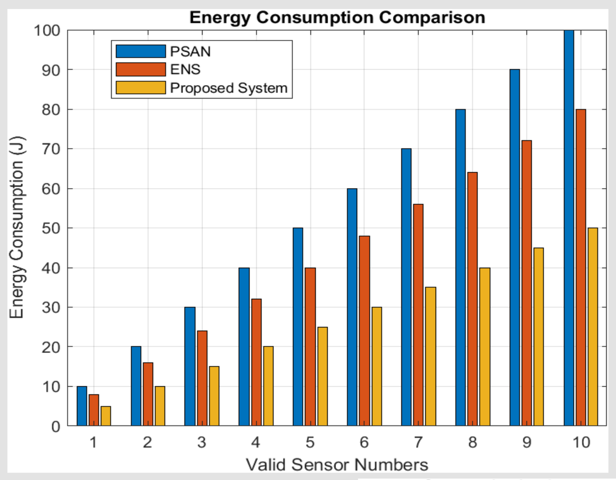


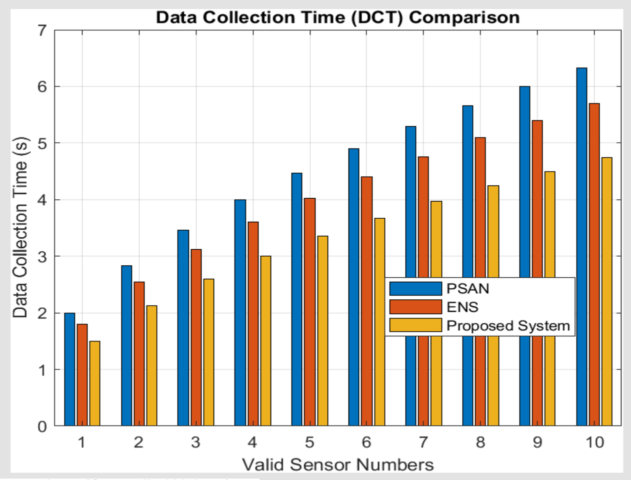
Comparison with LEACH & Sensing Algorithms

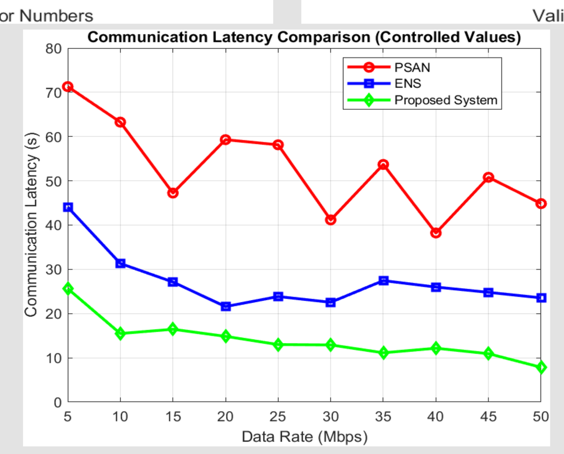












Conclusion

This research presents a novel framework to improve energy efficiency in wireless sensor networks by employing data aggregation techniques. By consolidating redundant data at the aggregator nodes, the number of transmissions is reduced, leading to lower energy consumption across the network. The proposed system introduces a gateway node that performs secondary data aggregation using edge computing after receiving data from cluster heads. This optimized data is then sent to the sink through a single, long-range transmission, further minimizing energy use. The proposed WSN framework markedly prolongs the network's lifespan by optimizing energy conservation. We evaluated the efficacy of our suggested method against a renowned clustering technique and two sensing algorithms. Our solution outperforms the LEACH protocol in energy dissipation, stability, data transfer to the base station, and network longevity, as evidenced by the comparative analysis. Furthermore, our framework surpasses the commonly utilized sensing algorithms, ENS and PSAN, in terms of communication latency, DCT, and energy usage. It is important to emphasize that this study concentrates on homogenous networks. Future study will seek to expand the dual data aggregation approach to heterogeneous networks and investigate additional performance indicators, including overhead, bandwidth consumption, and packet loss.

Reference

1. G. S. Nagaraja,1 K. Vanishree,2 and Farooque Azam Novel Framework for Secure Data Aggregation in Precision Agriculture with Extensive Energy Efficiency. Hindawi (https://doi.org/10.1155/2023/5926294) 24 February 2023.
2. Xiaomin Li , 1 Lixue Zhu , 1 Xuan Chu,1 and Han Fu2 Edge Computing-Enabled Wireless Sensor Networks for Multiple Data Collection Tasks in Smart Agriculture. Hindawi Journal of Sensors Volume 2020, Article ID 4398061, 9 pages https://doi.org/10.1155/2020/4398061 25 February 2020
3. Tahira Batool1, Atiq Ahmed2 , Dominique Gaiti2 Two level data centric aggregation scheme for wireless sensor networks Annals of Telecommunications (2024) 79:289–299 https://doi.org/10.1007/s12243-023-00984-5 8 September 2023