

Energy-Efficient Routing Algorithms for Wireless Sensor Networks in Smart Agriculture

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Abstract

The integration of Wireless Sensor Networks (WSNs) in agriculture has transformed traditional farming into a data-driven, efficient, and intelligent process. With the growing push towards precision agriculture, WSNs play a critical role in monitoring environmental parameters such as soil moisture, temperature, and humidity. However, energy consumption remains a major constraint due to the battery-powered nature of sensor nodes. This paper explores the use of energy-efficient routing algorithms in WSNs tailored for smart agriculture, focusing on Low-Energy Adaptive Clustering Hierarchy (LEACH) and its variants. The study highlights the significance of routing protocols in extending network lifetime, optimizing energy use, and ensuring reliable data transmission. It further evaluates the performance of these algorithms under real-world farming scenarios. Comparative analyses, tabular data, and schematic figures are included to demonstrate the impact of various techniques. This work aims to guide researchers and engineers in developing sustainable IoT-based smart farming systems.

Keywords: *WSN, energy optimization, LEACH protocol, smart farming, routing algorithm, precision agriculture*

INTRODUCTION

Precision agriculture leverages modern technologies to increase the efficiency and sustainability of agricultural activities. Wireless Sensor Networks (WSNs) are one of the core components that facilitate real-time monitoring of agro-ecological conditions. These systems consist of multiple distributed sensor nodes that are battery-powered and deployed across vast fields. The core challenge lies in maximizing the lifetime of these sensor nodes, as replacing or recharging batteries in field conditions is often impractical.

To address this, the development of energy-efficient routing algorithms becomes essential. These algorithms are responsible for determining the communication paths among sensor nodes and the base station. By minimizing unnecessary transmissions and optimizing the network structure, energy can be conserved significantly. Among these, the LEACH protocol and its variants have gained prominence for their ability to balance energy consumption and improve data throughput.

This paper provides an in-depth exploration of such routing algorithms, focusing on their application in smart agriculture. The study aims to illustrate the benefits and limitations of each method, providing tabular comparisons and schematic representations to support the analysis.

NEED FOR ENERGY EFFICIENCY IN SMART AGRICULTURE

Smart agriculture employs numerous sensors to collect data on soil health, plant growth, and weather conditions. As these sensors are deployed in remote and often large-scale environments, energy consumption becomes a bottleneck for continuous operation. Battery-powered nodes need to operate for extended periods, sometimes over entire growing seasons. Routing protocols must therefore minimize redundant communication, balance energy usage across the network, and avoid overburdening specific nodes.

Furthermore, energy efficiency contributes directly to network reliability and cost savings. Frequent node failures can lead to data loss, impacting the precision of agricultural decisions.

Hence, energy-aware routing is not just a technical enhancement but a necessity in smart agriculture.

Overview of Wireless Sensor Network Architecture in Agriculture

A typical WSN in agriculture includes multiple sensor nodes distributed across fields. Each node collects environmental data and forwards it to a central sink or base station.

These nodes consist of four key components: a sensing unit, a processing unit, a transceiver, and a power unit. The data collected is sent either directly or through multi-hop communication. The base station processes the information and sends it to cloud servers or farmer dashboards for actionable insights.

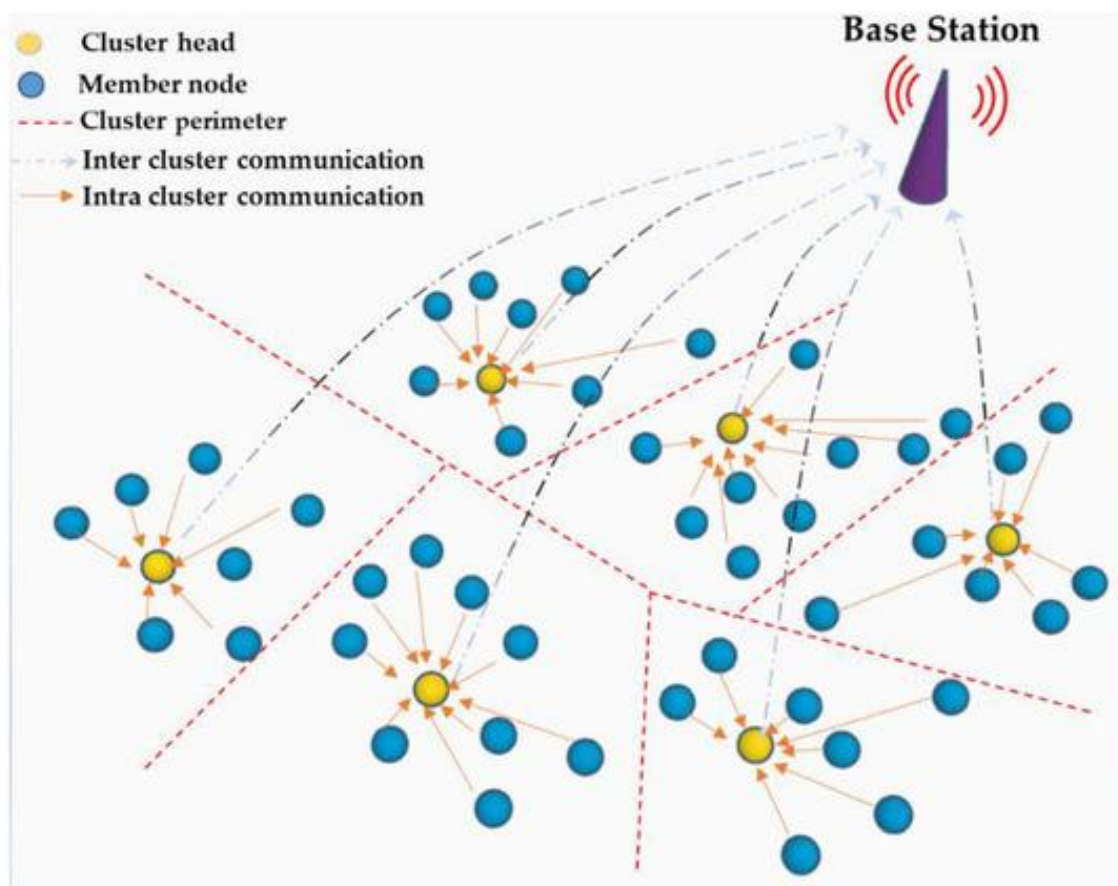


Figure 1: Structure of a Typical WSN in Smart Agriculture

CHALLENGES IN ROUTING FOR AGRICULTURAL WIRELESS SENSOR NETWORKS

Wireless Sensor Networks (WSNs) deployed in agricultural environments offer critical support in automating and optimizing tasks such as irrigation management, environmental monitoring, and pest control. However, implementing efficient routing mechanisms in such networks is fraught with challenges. These challenges directly impact network stability, energy efficiency, and overall performance. Understanding these obstacles is essential to designing energy-efficient protocols that are robust and scalable for real-world agricultural use.

One of the foremost challenges is energy constraints. Sensor nodes in WSNs are typically battery-powered and often placed in remote or hard-to-reach locations like large agricultural fields. Once deployed, it is usually impractical to recharge or replace these batteries frequently.

Therefore, energy becomes the most scarce and valuable resource in these networks. Routing protocols must be meticulously designed to reduce the number of transmissions, balance load across nodes, and avoid unnecessary data communication that can quickly drain the node's energy.

Another significant issue is node failures, which are common in agricultural settings. These nodes are exposed to harsh environmental conditions such as heavy rains, strong winds, and fluctuating temperatures. Additionally, agricultural activities like plowing or harvesting can damage or displace nodes. Wildlife and insects may also interfere with sensor functioning. These physical vulnerabilities lead to frequent node failures, which can disrupt routing paths and create data gaps unless the protocol can dynamically adapt to such disruptions.

Data redundancy is another pressing concern. In precision farming, multiple nodes often monitor the same parameter such as soil moisture or ambient temperature. If all nodes transmit their readings to the base station without any filtering or aggregation, a large volume of redundant data is produced. This not only wastes bandwidth but also leads to unnecessary energy consumption. Efficient routing protocols must include mechanisms to detect and eliminate redundancy by aggregating data at intermediate nodes.

Dynamic topology poses another layer of complexity in WSN routing. Agricultural fields are not static environments. Machinery such as tractors, irrigation systems, and autonomous drones may move through the field and interfere with node placement or communication paths. Seasonal changes like crop growth or flooding can also affect signal quality and link stability. The routing algorithm must be resilient to these dynamic changes and adapt in near-real-time to maintain network connectivity and performance.

Lastly, scalability remains a critical challenge. A small vegetable garden might need only a few nodes, but a commercial farm spanning several hundred hectares may require thousands. As the number of nodes increases, the routing protocol must ensure that energy consumption remains balanced and that latency does not increase significantly. Protocols that work efficiently in small networks often become unsustainable in large-scale agricultural deployments due to communication overhead, increased collisions, and uneven energy consumption.

Routing Algorithms for Energy Efficiency

Routing algorithms play a central role in determining the energy efficiency of Wireless Sensor Networks in agriculture. These algorithms define how data is transmitted from sensor nodes to the base station, and their effectiveness directly influences the network's operational lifetime.

While many routing protocols exist, those based on hierarchical clustering are generally considered the most suitable for smart agriculture due to their energy-conserving properties and scalability. One such protocol that has seen widespread adoption and adaptation is LEACH, or Low-Energy Adaptive Clustering Hierarchy.

LEACH stands out because it introduces the concept of clustering in WSNs, where nodes are grouped, and a designated leader known as the cluster head (CH) manages data communication within each group. This architecture significantly reduces energy consumption by minimizing the number of long-distance transmissions. Instead of every node communicating directly with the base station, only the CH performs this task after aggregating data from its cluster members. Moreover, LEACH rotates the CH role among nodes to prevent rapid battery depletion of any single node, thereby extending the network's lifetime.

LEACH (LOW-ENERGY ADAPTIVE CLUSTERING HIERARCHY)

The LEACH protocol has been a foundational model for energy-efficient routing in wireless sensor networks, particularly in the context of agricultural applications. It is based on the principle of hierarchical clustering and introduces randomness in cluster formation to distribute the energy burden across all nodes. LEACH operates in multiple rounds, and each round includes two main phases: the setup phase and the steady-state phase. Through these phases, the network continuously adapts and reorganizes itself to maintain energy efficiency and data integrity.

In the **setup phase**, a small percentage of nodes are selected as cluster heads. This selection is usually random and based on a predefined probability. Each chosen cluster head broadcasts its status to nearby nodes, which then decide which cluster to join based on signal strength. This results in the dynamic formation of clusters for the given round.

During the **cluster formation**, each non-cluster head node selects the CH with the strongest signal and informs it of its intent to join. The cluster head acknowledges and builds a Time Division Multiple Access (TDMA) schedule for data collection, which helps minimize collisions and saves energy by allowing nodes to sleep when not transmitting.

The **steady-state phase** involves the actual data collection and transmission. Each sensor node senses environmental parameters and sends the data to its designated cluster head during its assigned time slot. The cluster head then aggregates the collected data, compresses it, and transmits it to the base station in a single long-distance transmission. This data aggregation helps reduce redundant information and saves significant energy.

After a certain period or number of rounds, the network enters the **re-clustering phase**, where the process begins anew, and new cluster heads are selected. This rotation ensures that energy consumption is distributed evenly among all nodes, preventing premature death of any particular node due to excessive communication duties.

Advantages of Leach

LEACH offers several advantages that make it ideal for deployment in energy-sensitive environments such as agricultural fields. One of its major benefits is the **reduction in long-**

distance transmissions. Instead of every node communicating with the base station, only cluster heads are responsible for this task, thereby conserving energy at the individual node level.

Another advantage is the **balancing of energy load.** By randomly rotating the role of cluster head, LEACH ensures that the same nodes are not repeatedly overburdened. This uniform energy distribution enhances the network's overall stability and extends its operational life.

Additionally, LEACH contributes to an **increase in network lifetime** by enabling efficient data aggregation, reducing redundant transmissions, and leveraging sleep cycles for non-transmitting nodes. These mechanisms collectively ensure that WSNs in agriculture can function longer without manual intervention.

Limitations of Leach

Despite its benefits, LEACH is not without limitations. One of the primary concerns is the **random selection of cluster heads**, which may result in inefficient network configurations. For example, two or more cluster heads may be located near each other, or a cluster head may have very low residual energy, leading to quick failure.

Another limitation is that LEACH **does not consider the energy heterogeneity** of nodes. In real agricultural deployments, some nodes may have more battery life or solar charging capabilities than others. LEACH treats all nodes equally, which is not ideal for heterogeneous networks.

Additionally, LEACH **assumes equal energy distribution at initialization**, which may not hold true in practical deployments, especially if nodes are deployed at different times or have undergone varying levels of energy drain. This assumption limits LEACH's performance in real-world agricultural environments where node conditions are often non-uniform.

Furthermore, LEACH is more suited for networks with **static topology.** It does not efficiently handle dynamic changes in node positions or frequent node failures, which are common in agricultural fields due to environmental and operational factors. Thus, while LEACH provides

a solid foundation for energy-efficient routing, enhancements and adaptations are often necessary to address its shortcomings in smart agriculture settings.

Table 1: Comparison of Basic Routing Protocols Used in Agriculture WSNS

Protocol	Routing Type	Energy Efficiency	Scalability	Adaptability	Suitability in Agriculture
LEACH	Hierarchical	High	Moderate	Low	High
PEGASIS	Chain-based	Very High	Low	Low	Moderate
TEEN	Reactive	Moderate	High	High	High
HEED	Hybrid	High	High	Moderate	High
Direct Routing	Flat	Low	Low	Low	Low

MODIFICATIONS AND IMPROVEMENTS TO LEACH FOR SMARTAGRICULTURE

Although the LEACH protocol has significantly contributed to energy-efficient routing in Wireless Sensor Networks, it is not without limitations. Its reliance on random cluster head selection, equal energy assumptions, and its inability to handle heterogeneous networks or large-scale deployments effectively have prompted researchers to develop numerous modifications aimed at overcoming these challenges. These improvements focus on making LEACH more adaptable to the dynamic conditions of smart agriculture and more capable of prolonging the operational lifetime of sensor networks deployed across varying terrains and crop types.

One of the most impactful improvements is the **LEACH-C (Centralized LEACH)** protocol. Unlike the original LEACH that selects cluster heads randomly at the node level, LEACH-C employs a centralized approach where the base station takes responsibility for selecting cluster heads. The base station uses information such as the current energy levels of the nodes and their positions to determine an optimal cluster configuration. This centralized method leads to more efficient cluster head distribution, minimizing energy consumption and improving network performance. LEACH-C is particularly suitable for agricultural fields

where sensor deployment is semi-static and a central controller (like a gateway) can periodically optimize the network topology.

Another significant enhancement is **Multi-hop LEACH**, which addresses one of the critical issues with the original protocol—long-distance communication from cluster heads to the base station. In a large farm, distant CHs expend a considerable amount of energy when sending data directly to the base station. Multi-hop LEACH introduces intermediate cluster heads or relay nodes through which data can be forwarded, significantly reducing the energy required for long-range transmissions. This approach is especially beneficial for large-scale farms where nodes are deployed over expansive areas. It enables energy balancing and ensures that even distant nodes can participate in data communication without exhausting their energy resources rapidly.

A more context-aware version of LEACH is **Energy-LEACH**, which enhances the cluster head selection process by incorporating the residual energy of nodes. Instead of relying on probabilistic and random selection, Energy-LEACH prioritizes nodes with higher remaining energy for the role of cluster head. This modification prevents energy-depleted nodes from becoming cluster heads, thereby avoiding premature failures and extending the overall lifespan of the network. This is particularly effective in heterogeneous agricultural environments where different sensor nodes may have varying energy capacities due to solar panels or usage patterns.

Fuzzy-LEACH is a more intelligent and adaptive version of the protocol that leverages fuzzy logic to determine the most appropriate nodes to serve as cluster heads. It takes into account multiple parameters such as residual energy, node centrality, distance to the base station, and node density to make more informed decisions. Fuzzy-LEACH is especially valuable in scenarios where agricultural topologies are irregular or environmental conditions change rapidly. By using fuzzy inference systems, the protocol adapts to contextual information and provides better energy efficiency and network longevity.

These improved versions of LEACH demonstrate a concerted effort by the research community to tailor routing protocols to the needs of smart agriculture. Each modification

brings the system one step closer to real-world feasibility by addressing the energy, scalability, and reliability challenges inherent in wireless sensor deployments for agriculture.

Implementation Considerations for Agricultural Fields

Designing and deploying energy-efficient WSN routing algorithms in agriculture is not a one-size-fits-all solution. The characteristics of the farm—such as its size, topography, crop type, and density of sensor deployment—play a crucial role in determining which routing algorithm is most suitable. Practical implementation must take into account these physical and operational variables to ensure energy savings and network robustness.

In relatively flat agricultural fields, a simpler cluster structure can be implemented due to uniform distances between nodes and the base station. LEACH or Energy-LEACH protocols may work well in such scenarios as communication distances are manageable and obstacles are minimal. However, in terrains with significant elevation changes, such as hilly tea plantations or terraced farms, the network topology becomes more irregular. Routing in such cases must account for variations in transmission power and signal attenuation due to elevation and vegetation density. Here, protocols like Fuzzy-LEACH, which adapt to multi-criteria inputs, become more applicable.

Large-scale agricultural deployments that span dozens or hundreds of acres pose unique challenges. The distance between distant nodes and the base station can be excessive, and using single-hop communication is impractical due to high energy consumption. Multi-hop LEACH is better suited in such cases as it enables communication through intermediate nodes or cluster heads, significantly reducing power consumption per transmission.

Crop type also influences sensor deployment strategy and routing protocol design. For example, vineyards with high vertical structures may require sensors placed at different elevations, while paddy fields may need waterproof sensor enclosures. These differences affect signal propagation and energy usage patterns, making it essential for routing protocols to support heterogeneous environments and dynamic reconfiguration.

Node density is another crucial factor. In densely instrumented farms, load balancing becomes essential to avoid congestion and premature node failures. Routing protocols must be capable

of intelligent cluster formation and dynamic re-clustering to distribute communication loads evenly. Hierarchical protocols with adaptive cluster sizing and energy-aware decision-making are most effective in such scenarios.

FUTURE DIRECTIONS AND ADVANCEMENTS

As smart agriculture continues to evolve with technological advancements, the future of routing in wireless sensor networks is likely to be shaped by adaptive, intelligent, and sustainable solutions. The next generation of routing protocols is expected to leverage machine learning and artificial intelligence to make real-time decisions about cluster head placement, data aggregation, and route optimization.

Adaptive AI-driven routing protocols will use historical data and real-time environmental conditions to dynamically adjust routing paths, thereby ensuring optimal energy usage and resilience against node failures or changing network conditions. These systems will continuously learn from previous network states and optimize themselves without human intervention.

The integration of drones as mobile base stations or relay nodes presents another exciting avenue. Drones can fly over fields to collect data from remote clusters, significantly reducing the need for long-distance ground-based communication. This not only enhances energy efficiency but also improves coverage and reduces latency in large-scale farms.

Energy harvesting technologies are also poised to play a transformative role. Solar-powered sensor nodes that recharge during daylight hours can alleviate the energy constraint problem. Routing algorithms that consider energy harvesting patterns in their decision-making can enable perpetual sensor network operation with minimal human intervention.

In terms of data security and integrity, blockchain technology offers a decentralized and traceable way to manage routing data. By using blockchain-based ledgers, agricultural networks can ensure that the data collected and transmitted is tamper-proof, auditable, and trustworthy, which is especially important in precision farming where decision-making is highly data-driven.

Lastly, integrating Low-Power Wide-Area Network (LPWAN) technologies such as LoRaWAN or NB-IoT with WSNs will extend communication range, reduce power consumption, and enhance scalability. These technologies support long-range communication and can cover entire agricultural regions with minimal infrastructure.

In conclusion, the evolution of routing protocols for WSNs in agriculture is moving towards greater intelligence, autonomy, and sustainability. By incorporating AI, renewable energy, and emerging network paradigms, future systems will be capable of operating efficiently in diverse agricultural conditions while supporting the growing demands of precision farming.

CONCLUSION

Energy-efficient routing is foundational for the success of WSNs in smart agriculture. Among the many protocols available, LEACH and its variants offer promising results due to their cluster-based architecture. However, context-specific optimization is crucial. As the agricultural sector continues to embrace digital transformation, future innovations in AI, renewable energy, and hybrid networks will further enhance the effectiveness of WSNs in farming. The ultimate goal remains to ensure sustainability, productivity, and minimal energy consumption.

REFERENCES

1. Heinzelman, W. B., Chandrakasan, A. P., & Balakrishnan, H. (2000). Energy-efficient communication protocol for wireless microsensor networks. *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences*, 10(2), 3005–3014.
2. Yick, J., Mukherjee, B., & Ghosal, D. (2008). Wireless sensor network survey. *Computer Networks*, 52(12), 2292–2330.
3. Singh, S., Singh, P., & Gaurav, A. (2021). Energy-efficient routing protocols in WSNs for smart farming: A review. *International Journal of Wireless Networks and Broadband Technologies*, 10(3), 45–58.
4. Farooq, M. O., & Kunz, T. (2011). Operating systems for wireless sensor networks: A survey. *Sensors*, 11(6), 5900–5930.
5. Sharma, R., & Chauhan, R. (2020). Comparative analysis of LEACH and its variants in agricultural WSNs. *Journal of Agricultural Informatics*, 11(4), 21–30.

6. Verma, S., & Agrawal, R. (2019). LEACH-based protocols for energy optimization in WSN: A review. *Journal of Network and Computer Applications*, 126, 45–64.
7. Rawat, P., Singh, K. D., Chaouchi, H., & Bonnin, J. M. (2014). Wireless sensor networks: A survey on recent developments and potential synergies. *Journal of Supercomputing*, 68(1), 1–48.
8. Kim, J., & Park, H. (2019). Fuzzy-based cluster head selection algorithm in LEACH protocol. *Sensors*, 19(4), 1028.
9. Bandyopadhyay, S., & Coyle, E. J. (2003). An energy-efficient hierarchical clustering algorithm for wireless sensor networks. *INFOCOM 2003. Twenty-second Annual Joint Conference of the IEEE Computer and Communications Societies*, 3, 1713–1723.
10. Pantazis, N. A., Nikolidakis, S. A., & Vergados, D. D. (2013). Energy-efficient routing protocols in wireless sensor networks: A survey. *IEEE Communications Surveys & Tutorials*, 15(2), 551–591.
11. Singh, R., & Jha, A. (2021). Smart agriculture using WSN and energy-efficient clustering techniques. *International Journal of Advanced Computer Science and Applications*, 12(7), 75–82.
12. Manjeshwar, A., & Agrawal, D. P. (2001). TEEN: A routing protocol for enhanced efficiency in wireless sensor networks. *Proceedings of the 15th International Parallel and Distributed Processing Symposium*, 2001, 2009–2015.
13. Jain, V., & Mishra, M. (2020). IoT-based precision farming using sensor networks: Energy management through adaptive routing. *IEEE Internet of Things Journal*, 7(10), 9635–9645.
14. Chouhan, P., & Sharma, A. (2021). Data aggregation and energy-efficient routing in smart agriculture. *Journal of Green Technology*, 8(3), 55–67.
15. Liu, X., & Cao, H. (2017). Performance analysis of clustering protocols in WSN for smart agriculture. *Wireless Communications and Mobile Computing*, 2017, 1–10.
16. Gupta, D., & Meena, N. (2022). Multi-hop LEACH protocol for energy conservation in agricultural monitoring systems. *International Journal of Wireless Sensor Networks and Applications*, 14(1), 39–48.
17. Kumar, M., & Shukla, K. (2021). A review of energy-efficient routing protocols for agricultural WSNs. *Journal of Environmental Informatics Letters*, 5(3), 50–59.
18. Mehta, A., & Rathore, S. (2020). Sustainable routing in precision agriculture using WSNs. *Green IoT Applications*, 6(2), 82–90.

19. Joshi, R., & Verma, P. (2019). Comparative evaluation of energy-aware routing techniques in smart farming. *International Journal of Sensor Networks and Data Communications*, 8(1), 1–8.
20. Banerjee, T., & Goswami, R. (2022). Towards sustainable precision farming: Role of energy-efficient sensor networks. *Journal of Agricultural Science and Technology*, 24(2), 109–120.