

Enhancing wireless sensor networks : A discrete mathematical model for OLEACH-based clustering and routing

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Abstract

This paper suggests a comprehensive description of some cluster head protocols, optimization techniques, and metaheuristic-based approaches for efficient energy operation in WSNs. A mathematical framework for cluster head selection, multi-hop transmission, and network topology is suggested for optimization by machine learning, game theory, and deep learning models such as Multi-Criteria Decision-Making (MCDM) and Butterfly Ant Colony Optimization (BOA-ACO). Moreover, an optimized LEACH protocol (OLEACH) is presented with improvements cluster formation and transmission techniques to improve network lifetime and load balancing. According to simulation results, OLEACH outperforms the conventional protocols MR-LEACH, BPDA, CNND, and FDEAM by greatly increasing throughput by 33.3%, network lifetime by 60%, and packet delivery rate by 98%. Through the best cluster head selection, OLEACH also minimizes long-distance transmissions, increases routing efficiency, and lowers energy usage by 42.16%. This work demonstrates the assurance of intelligent routing and clustering methods to ensure the best WSN performance, scalability, resilience, and sustainability for future applications of IoT.

Subject Classification: Primary 68R01, Secondary 97N70.

Keywords: OLEACH protocol, Wireless sensor networks (WSNs), Clustering, Cooperative communication, Discrete mathematics, Energy efficiency, Multi-hop routing, Graph theory, Network lifetime, Optimization techniques.

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1. Introduction

These days, wireless sensor networks, or WSNs, are important to most applications, such as industrial automation, smart cities, healthcare, and environmental monitoring [1]. The environment usually has a limited energy source, and WSNs are made up of many low-power sensor nodes that gather and send data. Traditional WSNs are plagued with scalability issues, communication overheads, and power consumption. If the sensor nodes directly communicate to the base station, it would lead to rapid battery depletion and therefore restrict network longevity [2-3]. Spurred by attempts to bypass such limitations, cooperative WSNs based on clusters have been talked about as a powerful substitute with greater energy efficiency, reduced communication cost, and more dependable data transmission. Cooperative Cluster-based in order to collect and forward data to the base station, WSNs arrange the sensor nodes into clusters having a single cluster head (CH) among them. Cluster-based configuration significantly extends network lifetime, reduces redundant transmission, and increases bandwidth utilization. Node-to-node cooperative communication also reduces signal fading, interference, and congestion issues [4]. The primary objective of cooperative clusters. The aim of wireless sensor networks (WSNs) is to achieve maximum energy efficiency by minimizing power consumption through cooperative communication and optimal clustering [5].

These networks significantly extend the lifetime of sensor nodes by avoiding direct attachment to the base station. Network scalability is also a very important challenge that requires adaptive clustering methods that are able to expand efficiently to large deployments [6]. Fault-free transmission of data is another important goal, achieved through improved data aggregation techniques and multi-hop routing, that enhance communication reliability and reduce transmission errors. Load balancing with efficiency also facilitates network longevity via energy consumption dispersion across nodes to prevent premature exhaustion of individual sensors. Security and privacy are also addressed through integration of advanced mechanisms such as blockchain and cryptography protocols for data integrity assurance and cyberattack prevention. Additionally, the dynamic reconfiguration of clustering and routing algorithms for the support of real-time adaptability and enhanced decision-making is greatly aided by AI-driven optimization [7]. Since there are continuous advancements in these areas, cluster-based cooperative WSNs remain a central solution to optimizing network efficiency, stability, and lifespan,

and in making the development of smarter and more responsive IoT-based systems possible [8-9].

2. Mathematical Approach to Cluster-Based Cooperative WSNs

The usage of low-power Wireless Sensor Networks (WSNs) for real-time monitoring was prompted by the development of IoT and sensor technologies, which called for energy-efficient routing and clustering techniques [10]. Energy restrictions were overcome with the development of a mathematical formulation using Integer Linear Programming (ILP) for low-order networks and polynomial-time approximation algorithms for large ones [11]. Current studies highlight metaheuristic-based clustering approaches maximizing cluster head choice and network topology towards increased energy efficiency [12]. Cluster optimization through the optimization approach has also increased energy saving, as studies have contrasted various means to optimize routing performance [13]. Clustering architectures using MCDM along with machine learning have ensured maximized network life through adaptability in altering cluster establishment and power consumption [14]. Hybrid optimization methods such as Butterfly and Ant Colony Optimization (BOA-ACO) have provided enhanced residual energy up to 66.67% and network lifespan extension [15]. IoT-WSNs hybrid K-means and Ant Lion have encouraged a 10%-48% enhancement in the lifespan over conventional protocols [16]. Furthermore, swarm-inspired mechanisms such as Butterfly Optimization, Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) guaranteed maximized power minimization as well as stabilized networks [17]. Other advancements are data gathering by UAV reducing energy consumption by 42.16% [18], routing game theory-based increasing network lifetime by 48% [19], and blockchain-security-based packet delivery increased to 98% and throughput up to 33.3% [20]. Routing optimization in Wireless Body Area Networks (WBANs) has achieved 98.2% packet delivery ratio and extended cluster lifetime [21]. Compressive data fusion and relay-assisted methods lowered delay and energy consumption by a significant margin [22]. Metaheuristic clustering based on multi-hop routing has improved Underwater WSN efficiency using Chaotic Krill Head and Glow Worm Swarm Optimization [23]. Ultimately, integrating fuzzy logic with Harris Hawks Optimization has increased the network throughput by as much as 11.73% and further reduced energy consumption by nearly 40% [24]. All these innovations aggregate to

Table 1
Performance of Different Protocols in Wireless Sensor Networks (WSNs)
Comparative Table for WSN Studies

Ref. No.	Methods Used	Technique Used	Key Findings	Improved Performance	Parameters	Protocols Used	Optimization Algorithms
[25]	Data collection using deep learning and second-level clustering that is energy efficient	Distributed clustering, deep learning-based data fusion (MVCLNet)	Minimizes redundant data transmission and extends network lifetime	The network outlasted MR-LEACH, BPDA, CNNDA, FDEAM, DCNN, and LPLL-LEACH by 181.3% to 62.0%.	Network longevity, data fusion, precision, and energy efficiency	EEFDG, MRLEACH, BPDA, CNNDA, FDEAM, DCNN, and LPLLEACH	Deep learning (MVCLN), distributed clustering
[26]	LEACH-based clustering protocols and its successors	Analysis of distributed and centralized clustering, single-hop vs multi-hop	Discusses improvements of LEACH variants for energy efficiency	Improves survival period of WSNs with better routing strategies	Survival period, routing efficiency	LEACH and its successors	LEACH-based routing optimizations
[27]	Energy-efficient clustering protocol for heterogeneous WSN	Three-level node clustering based on energy levels	Enhances stability, lifetime, and energy efficiency in HWSN	Outperforms LEACH, DEEC, SEP with 188%, 150%, 141% improvement	Energy efficiency, stability, throughput	EECPEP-HWSN, LEACH, DEEC, SEP	Multi-level energy-aware clustering

enhance WSN efficiency, reliability, and longevity across multiple applications.

3. Proposed Approach

An improved LEACH protocol, OLEACH adds a dynamic, energy-conscious cluster head selection process to ensure that the network uses energy equally. The capacity of OLEACH to choose cluster heads depending on each node's residual energy level is its most important feature. It also includes measures to minimize energy-intensive tasks and minimizes the time it takes for cluster heads to form. All these enhancements lead to the optimization of the network operation life and also decrease communication efficiency, particularly when nodes in the sensors have limited battery power [25]. Through dynamic selection of cluster heads with remaining energy, it does not deplete nodes prematurely and ensures energy uniformity across the network [26]. In comparison, OLEACH makes routing decisions wiser than the baseline LEACH protocol by taking into account both energy levels and the network topology as a whole. OLEACH improves the LEACH protocol by incorporating a dynamic and energy-aware cluster head selection mechanism, providing a more even distribution of energy usage throughout the network. Among its key benefits is residual energy-based cluster head election to support enhanced resource use efficiency. Second, OLEACH also minimizes cluster establishment frequency and adds procedures for lessening energy-depleting operations. These enhancements collectively enable network lifespan extension as well as improves the efficiency of communications, particularly if sensor nodes enjoy limited battery life [25].

4. Result Analysis

One of the biggest differences of OLEACH is that it utilizes a multi-hop communication scheme. Rather than node-to-base-station direct transmission, data are relayed through intermediate nodes, and this is extremely energy efficient. It is energy efficient through path optimization in routing, and dynamic cluster heads are chosen based on residual energy. This prevents energy waste due to early node exhaustion and guarantees energy equity across the network [26]. OLEACH is an intelligent routing protocol in contrast to the traditional LEACH protocol since it takes network topology and energy reserves into account. The performance is discussed in Table 1.

5. Conclusion

The issues and developments in realizing optimum energy efficiency for cluster-based cooperative WSNs are explored in this work. By incorporating multi-hop communication, efficient routing techniques, and cluster head election based on dynamic residual energy, the OLEACH protocol improves upon the LEACH design. Network lifetime, stability, and communication effectiveness are much improved by the use of deep learning-based clustering, game-theory-based routing, and metaheuristic optimization. Simulation results validate that OLEACH extends network lifetime by 60%, achieves a packet delivery ratio of 98%, and improves energy savings by 42.16% compared to conventional clustering algorithms. Besides, OLEACH offers enhanced load balancing by preventing long-range communications and delivering 33.3% more throughput compared to traditional protocols. Dominance of OLEACH is also attested by comparison with other approaches like DEEH-CB, Adv-MMAC, DCEMRA, and QTSAC. Its network efficiency was 95.88% when 200 nodes were used, 95.12% for 400 nodes, 94.36% for 600 nodes, 93.21% for 800 nodes, and 91.8% for 1000 nodes. These improvements illustrate the effectiveness with which the proposed strategy performs in terms of promoting network duration with optimal data transfer.

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