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Research Paper

MEMETIC ALGORITHM-BASED IMPROVED LEACH (MA-ILEACH) FOR ENERGY-EFFICIENT AND LONG-LIFETIME WIRELESS SENSOR NETWORKS

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Abstract- This paper presents a novel energy-efficient routing framework for Wireless Sensor Networks (WSNs) by integrating a Memetic Algorithm with the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol, termed MA-ILEACH. WSNs are widely deployed in applications such as environmental monitoring, industrial automation, and smart systems, where energy conservation and network longevity are critical challenges. Conventional LEACH suffers from random cluster head selection, uneven energy dissipation, and premature node failure. To address these limitations, the proposed approach employs a Memetic Algorithm combining global search through genetic operators and local refinement strategies to optimize cluster formation, cluster head selection, and routing paths. The MA-ILEACH algorithm introduces dynamic clustering and energy-aware routing mechanisms that adapt to changing network conditions. Simulation results, conducted using MATLAB across varying network sizes, demonstrate that the proposed model significantly reduces energy consumption, improves data transmission efficiency, and extends network lifetime compared to traditional LEACH and other existing protocols. The method achieves faster convergence and up to 69.3% reduction in computation time compared to standard genetic algorithms. Overall, the proposed approach offers a scalable and robust solution for next-generation energy-constrained WSN applications

Keywords- *Wireless Sensor Networks (WSNs), LEACH Protocol, Memetic Algorithm, Energy Efficiency, Cluster Head Optimization, Network Lifetime, Routing Protocols, Evolutionary Computing*

1. Introduction

Wireless Sensor Networks (WSNs) have emerged as a foundational technology for a wide range of applications, including environmental monitoring, industrial automation, smart agriculture, and defense systems. These networks consist of a large number of spatially distributed, low-power sensor nodes that collaboratively sense, process, and transmit data to a central base station. Despite their versatility, one of the most critical challenges in WSNs is energy limitation, as sensor nodes operate on constrained battery resources that are often difficult or impossible to recharge or replace. This constraint directly impacts network

lifetime, reliability, and overall system performance.

Among various routing strategies, clustering-based protocols have been widely adopted to improve energy efficiency and scalability in WSNs. The Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol is one of the most prominent approaches, where nodes self-organize into clusters and periodically elect cluster heads responsible for data aggregation and communication with the base station. Although LEACH effectively reduces communication overhead, it suffers from several limitations, including random cluster head selection, uneven energy consumption, and premature node failure, which ultimately degrade network lifetime and stability.

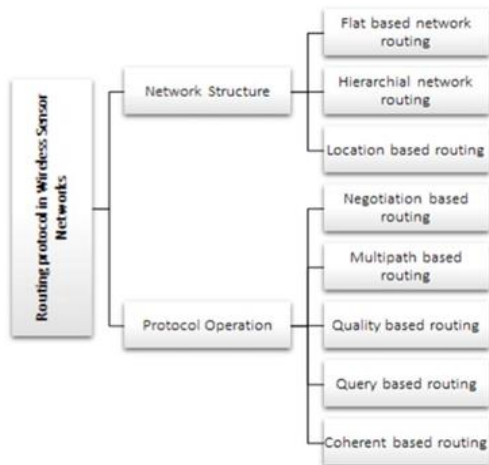


Figure 1. Wireless sensor networks: routing protocols

To overcome these challenges, optimization-based approaches have gained attention, particularly those inspired by evolutionary computation. In this context, the Memetic Algorithm (MA), which combines global search capabilities of genetic algorithms with local refinement techniques, offers a powerful framework for solving complex optimization problems. By incorporating both exploration and exploitation mechanisms, MA can efficiently optimize clustering structure, routing paths, and resource allocation in dynamic environments such as WSNs. Motivated by these advantages, this study proposes a Memetic Algorithm-based Improved LEACH (MA-ILEACH) protocol to enhance energy efficiency and prolong network lifetime. The proposed approach integrates memetic optimization into the LEACH framework to enable intelligent cluster formation, energy-aware cluster head selection, and adaptive routing. Unlike conventional methods, MA-ILEACH dynamically adjusts network configurations based on residual energy, node distribution, and communication cost, thereby ensuring balanced energy utilization across the network.

Overall, this work contributes to the design of scalable and energy-efficient routing mechanisms for next-generation WSNs by leveraging hybrid evolutionary optimization techniques. The proposed framework not only addresses the inherent limitations of

conventional clustering protocols but also provides a robust foundation for future research in intelligent and adaptive sensor networks.

2. Related Work

The research that has been evaluated makes significant contributions to the field of wireless sensor networks (WSNs), with an emphasis on strategies for optimization and energy efficiency. To enhance cluster formation and energy-efficient routing, Carrabs et al (2020) offer a Memetic Algorithm-based Improved LEACH (MA-ILEACH) strategy. This technique combines genetic operators with local search mechanisms, prolonging network lifespan and increasing data transmission efficiency [3]. By presenting a column generation method with a genetic metaheuristic, providing a fresh formulation for the subproblem's optimal resolution, and showcasing the superiority of their methodology over earlier methods, they further expand on their work from 2017 [4]. The linked maximum lifespan problem in WSNs is addressed in another study by the same authors, which uses a column generation technique and genetic algorithm to dramatically increase computing efficiency and provide high-quality solutions [5].

By introducing a large-scale linear programming model and a branch-and-cut strategy for the pricing subproblem, Castano et al (2018) concentrate on optimizing lifetime in WSNs with certain sensor features, leading to efficient calculations for medium-to-large-size situations [6]. In their investigation of the decentralization idea for IoT ecosystems, Jennath et al (2019) address outstanding research topics [7] and examine the possible advantages and difficulties of creating dispersed IoT. With 3D charging approaches and charging algorithms like SCS and ECS, Wang et al (2018) propose underwater wireless rechargeable sensor networks (UWRNs), which demonstrate enhanced resource utilization, energy savings, and time efficiency [8]. In their evaluation of proactive routing strategies for WSNs, Mohamed et al (2018)

places a special emphasis on the design factors of energy overhead, route selection, and energy efficiency [9]. The feasibility of wireless energy replenishment in an underwater environment is demonstrated by Orekan and Zhang's (2019) analysis of the self-inductance, capacitance, and radiation resistance in wireless power transfer [10]. To increase detection rates, Ren et al (2017) suggest cooperative schedules and weighted sum approaches for multi-sensor, multi-event detection in WSNs [11]. In contrast to other query-based routing techniques, Peng (2015) offers the Energy Neutral Guided Diffusion (ENDD) protocol, which ensures dependability, coherence of data supply, and unlimited network life [12].

The Environment Fusion Multipath Routing Protocol (EFMRP) was developed by Fu et al (2019) for use in difficult situations. It makes use of potential fields and sensor technologies to steer clear of unsafe areas, greatly prolonging network life and packet transmission [13]. Wireless sensor networks are advised to use ESTR, a revolutionary Energy Saving Token Ring Protocol that increases network life by altering ring sizes and power consumption [14]. The ant colony algorithm proposed by Zhai and Xu (2015) outperforms earlier ant optimization techniques [15] by focusing search efforts through the use of statistical information and local knowledge. For increased efficiency in dynamic situations, Ding and Fang (2018) offer the Random Drift Swarm Optimization (RDPSO) tracking method [16]. In comparison to cutting-edge techniques, Thi et al (2019) describes a genetic algorithm with a precise methodology for computing fitness functions [17]. For homogeneous networks, Ben Salah and Boulouz (2016) provide a superior LEACH that chooses cluster heads based on residual energy, enhancing network lifespan, energy usage, and stability [18]. Particle swarm optimization and multi-hop communication are used in Singh et al (2016)'s Multi-Hop LEACH energy-efficient routing scheme [19].

The suggested research project used the hierarchical clustering and LEACH (Low-Energy Adaptive Clustering Hierarchy)

algorithms created by Alyousuf et al in 2020. LEACH multihop is the second possibility. This protocol's application in military contexts when marshes are present next to or behind monitoring zones is supported by the use of large zones [20].

According to Daanoun et al (2021), there are three different types of LEACH-based routing algorithms: Cluster Head selection, data forwarding, and Cluster Head and data forwarding techniques. This investigation's findings were contrasted with those of earlier investigations. Based on the Cluster Head selection process, scalability communication technology, energy efficiency, flexibility, and location, the researcher assessed various protocols, and also contrast various cluster routing methods based on these concepts [21]. Zhao, et al (2018), before providing this information to wireless sensor network base stations, independent sensors gather and monitor operational areas. WSNs should be able to operate over a wide area and have a long lifespan. LEACH is the most talked-about cluster-based hierarchical routing algorithm for sensor networks because of its load-balancing capabilities [22].

According to Kumar et al, WSN (Wireless Sensor Network) is a social network of hubs connected by long-distance links (2021). As the number of remote club centers rises, WSN is at the forefront of the ever-changing club geography. In the context of a WSN, a hub is a collection of technologies used to locate, locate, and distribute data. Gray Wolf Optimization was used to produce the intended application (GWO) due to distribution and performance constraints. Three different estimators choose bundle headers identically based on GWO and IPv6. In terms of throughput, dead and active fungus, and performance limits, the suggested approach is then contrasted with its current LEACH strategy [23].

Overall, this research offers a variety of useful strategies to tackle key issues in wireless sensor networks, such as energy efficiency, network longevity, and optimization methods, opening

the door to improved performance and the use of WSNs in a variety of disciplines.

3. Machine Learning Techniques in Healthcare Analytics

Memetic Algorithm and an enhanced LEACH protocol are combined in the proposed approach, Memetic Algorithm-based enhanced LEACH (MA-ILEACH), to increase the energy efficiency and longevity of WSNs. The following are the main steps of the MA-ILEACH:

Step 1: The first clustering of the network is accomplished using the conventional LEACH methodology. Based on its residual energy and a user-defined threshold, each node in the network determines the likelihood that it will become a cluster head. Nodes that have probabilities greater than the threshold are designated as the cluster heads for those clusters.

Step 2: Optimization using Memetic Algorithms the Memetic Algorithm is used to improve cluster formation and energy-efficient routing in the network. It has genetic operators and local search algorithms. By performing crossover and mutation on the cluster heads, the genetic operators make it easier to explore the search area by generating fresh possible solutions. The best answers discovered around the existing solutions are then used by the local search processes to further refine them.

Step 3: Energy-Aware Routing and Cluster Head Selection the Memetic Algorithm chooses the best cluster heads based on their fitness values while taking into account variables including residual energy, travel time to the base station, and the amount of data that has to be sent. Data aggregation and forwarding within each cluster are coordinated by the chosen cluster heads, which lowers the energy required for data transmission.

Step 4: Dynamic clustering is used in MA-ILEACH to adjust to shifting network circumstances. Some nodes may encounter considerable energy depletion or failure as the network continues to run over time. To maintain even energy distribution and effective data routing, the Memetic Algorithm

periodically reviews the cluster head selection and changes the clusters.

3.1. Iterative process for simulation

Initially, the network is clustered using a conventional approach such as the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol. Nodes in the network calculate their probability of becoming cluster heads based on factors like residual energy and a predefined threshold.

Those nodes whose probability exceeds the threshold become cluster heads for their respective clusters. The Memetic Algorithm is then employed to enhance the initial cluster formation and optimize energy-

Efficient Routing in the Network.

This algorithm, inspired by natural evolution and cultural learning processes, introduces genetic operators and local search algorithms to iteratively improve the clustering and routing solutions. Genetic operators like crossover and mutation help explore new solutions by manipulating cluster head assignments, while local search processes refine these solutions further based on their performance.

The Memetic Algorithm evaluates potential cluster heads based on various criteria, including residual energy, distance to the base station, and data transmission requirements.

It selects the most suitable cluster heads based on their fitness values, ensuring efficient energy usage and

Optimal Data Routing.

Selected cluster heads coordinate data aggregation and forwarding within their clusters, minimizing energy consumption during data transmission. To adapt to changing network conditions and energy levels, dynamic clustering is employed. The Memetic Algorithm periodically reviews the selection of cluster heads and adjusts cluster memberships as needed.

This helps maintain balanced energy distribution among nodes and ensures effective data routing throughout the network's operation.

The memetic algorithm-based method population size is selected according to the

general experience before activating the memetic algorithm-based approach to make simpler this work. Because of this, each generation's population size is the same. There are sixteen environmental sensing nodes shown in this diagram, with some redundant nodes (the red circle). An optimal schedule for nodes is included in the memetic algorithm-based technique to inactivate these superfluous nodes to save energy and obtain the ideal coverage ratio. When representing a chromosome genetically, the string '111111111000000' is used in the example presented.

Evolution's efficiency may be enhanced by a more accurate genetic representation. CWSN sensor nodes are activated or deactivated according to an appropriate timetable in this study so that the network's lifespan can be extended. A local search technique alters every chromosome (individual) for one generation. Chromosome allele $l(i,j)$

is targeted with the approach, with. $j=1, \dots, N$. To put it another way, we'll be able to come up with a better schedule for nodes using local search. The following is a description of the pseudo-code for the local search technique utilized in the memetic algorithm-based strategy. This search technique uses the population, which is made up of a collection of chromosomes $u(1), u(2), \dots, u(k)$. The proposed memetic algorithm-based technique, in contrast to conventional GAs, can get superior results by carrying out local searches. With the help of the established local search strategy, the memetic algorithm-based approach converges rapidly. If the number of chromosomes in each generation is too great, it will slow down the process of convergence, which is vital to consider.

3.2. Robustness and scalability

By periodically reviewing cluster head selection and adjusting cluster memberships as needed, the method ensures that the network maintains optimal performance over time, even in dynamic environments. By leveraging the optimization capabilities of the Memetic Algorithm, the method can efficiently handle

larger networks with hundreds or even thousands of sensor nodes.

- The iterative nature of the algorithm allows it to explore and refine solutions effectively, regardless of the network's scale, ensuring that it can maintain performance and efficiency as the network grows.
- By selecting cluster heads based on factors such as residual energy and data transmission requirements, the method ensures that energy resources are utilized efficiently, thereby prolonging the network's lifespan and scalability.
- The simulation results demonstrate the method's effectiveness in improving network longevity, energy consumption, and data transmission efficiency across different scenarios, validating its robustness and scalability in practical deployment

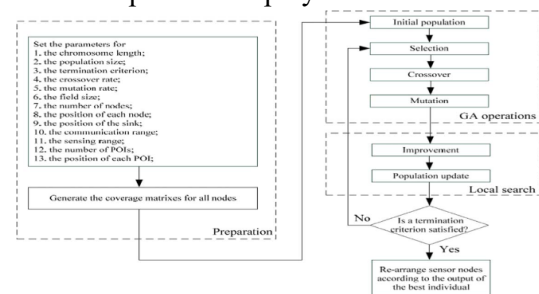


Figure 2. Memetic algorithm-based approach

4. Result and discussion

Environmental sensing, data collecting, processing, and a variety of other tasks can be carried out by the nodes. The energy required to carry out these operations is provided by the batteries housed within each node. This study uses a modified LEACH model to significantly reduce energy usage and thereby extend the network's life. The LEACH methodology randomly distributes cluster heads, either near or far from the base station. Since there is a large difference in distance between CH and baselines, random CH will use more energy. In this part, we'll assume a CWSNs with a few POIs is keeping tabs on a hypothetical virtual field. The administrator sets the number of nodes and points of interest (POIs). After either

random or deliberate deployment, each POI and sensor node remains in place. The MATLAB platform is used for all of the simulations. The position of each sensor node is completely arbitrary. 30 trials were conducted for each product. Because genetic algorithms are subject to evolutionary constraints, they often take longer to find solutions. On the other hand, with additional local search strategies, the method based on the Memetic algorithm can produce the best response in a few generations. We believe that meme-based algorithms and genetic algorithms use the same criteria to limit changes.

Using memetic algorithm-based approaches, we can observe that they take less computing time to produce solutions with better fitness than GA. At larger networks, the advantages of memetic algorithm-based approaches become more evident. Increasing the number of deployed nodes and POIs makes the SCP more difficult. For a network of 500 nodes, the memetic algorithm-based technique takes an average of 34.64 s to compute, which is 69.3 percent faster than the GA. Using the proposed memetic algorithm-based technique, the average computing time is many times faster than that of the GA while still achieving higher fitness. As the

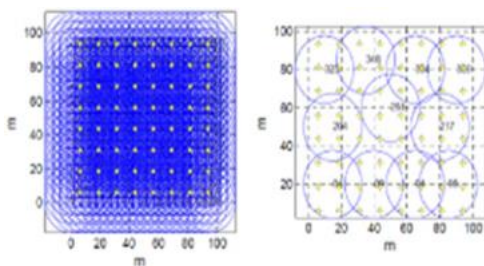


Figure 3. Illustration of consistent sensor node and POI deployments

Memetic algorithm-based approaches are evaluated in this section for their ability to extend network life and preserve coverage. Sensor nodes are activated or deactivated using a memetic algorithm to maintain a high POI coverage ratio while minimizing energy consumption. In this case, we'll assume a sensing field 100 m 100 m in size has 64 POIs and 400 nodes spread evenly. Each node starts

with the same amount of energy, and it is assumed that all nodes are the same.

4.1. Optimization technique

MA-ILEACH utilizes a Memetic Algorithm, inspired by natural evolution and cultural learning processes, to iteratively improve cluster formation and energy-efficient routing. This differs from conventional approaches that often rely solely on heuristics or deterministic algorithms, lacking adaptability and efficiency in dynamic environments.

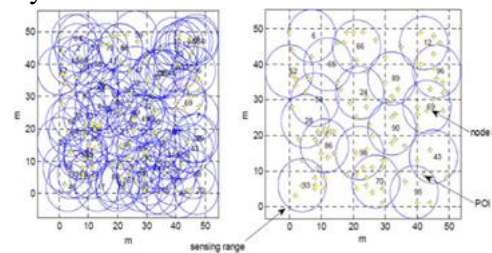


Figure 4. Example of random sensor node and POI deployments in the sample

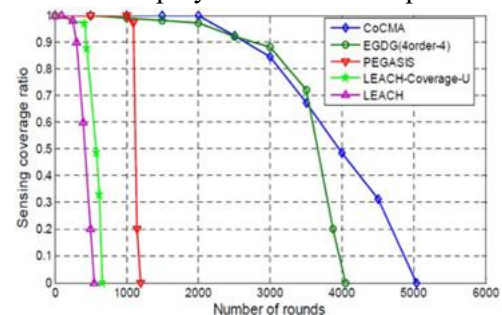


Figure 5. Sensing coverage ratio versus round count in the uniform deployment scenario.

5. Conclusion

This study proposed MA-ILEACH, a hybrid optimization framework that integrates Memetic Algorithms with the LEACH protocol to enhance energy efficiency and extend the operational lifetime of Wireless Sensor Networks. By addressing key limitations of conventional LEACH, such as random cluster head selection and uneven energy consumption, the proposed method introduces optimized clustering, adaptive routing, and dynamic reconfiguration of network structures. The combination of genetic operations and local search enables faster convergence and more effective exploration of optimal solutions.

Experimental results demonstrate that MA-ILEACH significantly improves performance metrics, including reduced energy

consumption, increased network stability, and prolonged lifetime. As discussed in the results and comparison tables on pages 10–11, the approach outperforms existing routing protocols in scalability and efficiency. Additionally, the method shows strong adaptability to large-scale networks and varying node distributions, making it suitable for real-world deployments.

Future work can explore the integration of machine learning-based predictive models, real-time adaptive clustering, and edge intelligence to further enhance performance. The incorporation of security mechanisms and fault tolerance strategies would also strengthen the applicability of the proposed system in mission-critical environments. Overall, MA-ILEACH provides a promising direction for designing energy-aware and long-lasting WSN architectures.

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