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Enhancing LEACH Protocol with Multi-Criteria Decision Making for Prolonged Network Lifetime in WSNs

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ABSTRACT

Wireless Sensor Networks (WSNs) have become a crucial solution for monitoring across diverse environments and consist of tiny sensor nodes that autonomously gather data on the environment. Energy depletion is a looming challenge, as sensor nodes rely heavily on their batteries, and once exhausted, the entire network can collapse prematurely. The Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol is a cornerstone in energy-efficient routing protocols for WSNs. However, the Cluster Head (CH) selection process in the traditional LEACH protocol relies on a probabilistic model for CH selection, where each sensor has an equal chance of becoming a CH based on a fixed threshold. To address these issues, this paper proposes an enhanced version of the LEACH protocol by employing a Multi-Criteria Decision-Making (LEACH-MCDM) process for CH selection. Instead of relying on random probabilities, the proposed protocol incorporates three key factors: Residual Energy (RE), Distance to the Base Station (DBS), and Node Degree (ND). Nodes with higher RE, shorter DBS, and an optimal ND are more likely to be selected as CHs. Compared to the traditional LEACH, the proposed method significantly improves the network's lifetime by evenly distributing energy consumption and reducing the risk of premature node failure. Simulation results demonstrate the enhanced protocol's ability to sustain more operational rounds and achieve higher energy efficiency.

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1. INTRODUCTION

Wireless Sensor Networks (WSNs) have become one of the most promising solutions for real-time monitoring in various environments which are composed of a tiny sensor nodes that can be self-organized to collect data about the surroundings, including temperature, motion, and other phenomena, and send the received data to the Base Station (BS) for analysis [1–3]. WSNs are applied in different areas such as agriculture [4], food control [5], healthcare [6], smart transport systems [7], industrial automation [8], military surveillance [9], and many others. Yet, despite their widespread utility, WSNs face significant hurdles. However, the individual nodes are somewhat limited in their battery life, computational abilities, and bandwidth capabilities. Energy depletion is another issue which is evident since sensor nodes are dependent on batteries where in case they run out the entire network may crumple at an early stage. Therefore, optimizing energy consumption, especially during communication phases, is essential to extend network longevity [10–12].

The Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol [13] serves as an essential component of the energy-efficient routing protocols for WSNs. LEACH design focuses on clustering, where more sensors are combined into clusters and each with its Cluster Head (CH). The CH is responsible for pooling information from its correspondingly affiliated nodes and forwarding it to the BS, which drastically reduces direct contact of individual nodes with the BS. However, the selection of CHs in the traditional LEACH protocol possesses a few significant limitations. LEACH in an attempt to address the problem of CH selection employs a purely probabilistic model of CH election in which each node is equally likely to be chosen as a CH based on a specified probability threshold. This randomness, though presented through basically straightforward procedures, can cause a lot of waste. If a node with little residual energy is assigned as a CH, then it drains energy quickly. Similarly, nodes close to the BS consume energy in transmission. In addition, LEACH fails to consider node degree, therefore forming quite unbalanced clusters where some CHs receive and forward much more data traffic than others. These disadvantages reduce the overall efficiency and network life in WSNs in general.

To resolve these problems, this paper introduces a new improved LEACH protocol that uses a Multi-Criteria Decision-Making process (LEACH-MCDM) to select the CHs. Instead of relying on random probabilities, the proposed protocol incorporates three key factors: Residual Energy (RE), Distance to the Base Station (DBS), and Node Degree (ND). Each factor is allocated a weighted coefficient α, β, and γ to reflect its importance in the CH selection procedure. Nodes with shorter DBS, higher RE, and an optimal ND (i.e., balanced connectivity) have a higher chance of being chosen as CHs. Compared to the traditional LEACH, this method significantly improves the network's lifetime by distributing energy consumption more evenly and reducing the risk of premature node failure. Simulation results demonstrate the enhanced protocol's ability to sustain more operational rounds and achieve higher energy efficiency, making it a promising solution for energy-constrained WSN applications.

2. RELATED WORK

Over the years, several research works have been dedicated to energizing protocols for WSNs to maximize their energy efficiency and network lifetime, with special emphasis on cluster-based routing protocols. LEACH [13] is one of the initial protocols that presented the possibility of adopting a probabilistic model to select the CHs and to provide for their periodic change to equitably share energy load between nodes. Despite its impact, LEACH's limitations (such as the random selection of CHs without consideration of RE or DBS) have prompted numerous enhancements to optimize performance and extend network longevity.

Subsequent improvements like LEACH-Centralized (LEACH-C) [14] have proposed a centralized approach for CH selection, allowing the BS to compute clusters based on node positions and energy levels. This centralized model improves energy distribution but can increase the computational load on the BS, potentially leading to higher operational costs in large-scale networks. Xu *et al.* [15] an advanced version of LEACH protocol known as E-LEACH to reduce energy and extend the longevity of WSNs. E-LEACH addresses the limitations of LEACH by introducing a more intelligent CH selection mechanism that take in consideration the remaining energy of nodes. Additionally, it adjusts the round time based on the optimal cluster size to balance energy consumption. Liu and Ravishankar [16] proposes a Genetic Algorithm-based Adaptive Clustering Protocol (LEACH-GA) to improve the energy efficiency in WSNs, which addresses the limitation of the traditional LEACH protocol by dynamically determining the optimal probability for CH election. Genetic algorithm was employed to optimize the energy consuming per round. By adapting the cluster formation process to the network conditions, LEACH-GA demonstrates improved network longevity compared to LEACH and other protocols. Karthikeyana and Senthilkumar [17] proposed a protocol that combining the genetic algorithm with the LEACH protocol to enhance the energy efficiency of WSNs. GAO-LEACH protocol optimizes CH selection by considering RE and other relevant factors(throughput, Packet Delivery Ratio, latency, and energy usage). Through simulation results, GAO-LEACH demonstrates significant improvements over traditional LEACH and DEEC protocols in terms of energy consumption, packet delivery ratio, throughput, and network latency. Radhika and Sivakumar [18] utilizes a micro genetic algorithm to optimize CH selection, addressing the limitations of traditional LEACH protocols (μGA-LEACH) to enhance energy efficiency and extend network longevity in WSNs. designed . This protocol By considering factors like RE, location, and network topology, μGA-LEACH achieves a more balanced distribution of energy consumption. Simulation results demonstrate that μGA-LEACH outperforms existing protocols like LEACH, GADA-LEACH, LEACH-

GA, and LEACH-C in terms of network lifetime and energy consumption. This makes it a promising solution for energy-constrained WSNs. Abu Salem and Shudifat [19] proposed an enhanced LEACH protocol that addresses the limitations of the original protocol by considering the distance between the BS and the CHs. Their simulation results showed that the proposed approach can reduce power consumption for both CHs and the entire network compared to the original LEACH protocol. Dwivedi and Sharma [20] proposed improved LEACH protocol named as EE-LEACH, which was to improve the energy efficiency and lifetime of WSNs. EE-LEACH uses fuzzy logic based approaches for most of the decisions such as the decision on cluster formation and the decision on CH selection. EE-LEACH as well aims to prolong the network life-time by distributing the energy consumption depending on parameters such as remaining energy, the distance to the BS, and the density of the nodes Mohammed *et al.* [21] proposed a routing protocol S-LEACH for WSNs. S-LEACH overcomes the limitations of the traditional LEACH protocol by splitting the network area into sectors, which reduces the transmission distance between the BS and the nodes. This approach leads to significant energy savings, as energy consumption is directly proportional to transmission distance. Additionally, S-LEACH uses a CH selection process based on remaining energy, which makes energy consumption more uniform across nodes. Kumar *et al.* [22] proposed ACHs-LEACH, an enhancements LEACH protocol which improved the network lifetime and energy efficiency. The ACHs-LEACH protocol focused on optimizing CH selection and data aggregation to reduce energy consumption. Simulation results demonstrate that the proposed enhancements improve network lifetime, energy efficiency, and packet delivery ratio compared to traditional LEACH. Sinde *et al.* [23] proposed an Enhanced-LEACH (E-LEACH), to improve the network lifetime and energy efficiency in WSNs. E-LEACH address the limitations of traditional LEACH by introducing a parallel optimization approach using Grey Wolf Optimization (GWO) and Discrete Particle Swarm Optimization (D-PSO) for optimal CH and helper CH (HCH) selection. Additionally, to prevent energy wastage in large clusters, the proposed E-LEACH also controls the size of a cluster. Moreover, the paper employed an energy-aware Time Division Multiple Access (TDMA) scheduling mechanism, in which the CH divides its coverage area into 24 sectors and assigns time slots to nodes for alternate sectors, to ensure balanced energy consumption by alternating between sense, transmit, and sleep states. kKang *et al.* [24] proposed LEACH-eXtended Message-Passing (LEACH-XMP), to enhance energy efficiency and prolonging the network lifetime in WSNs. To mitigate the weakness of such existing LEACH protocol, LEACH-XMP presented a more realistic nonlinear energy consumption model for CH nodes depending on both transmission energy and digital-processing energy, as well as compression rates of data depending on the correlation of collected data. By utilizing a distributed message-passing approach, the LEACH-XMP allows for low computational burden and rapid convergence during the cluster formation process. The ability of the algorithm to deal with the nonlinearity of the energy model accordingly means that the algorithm is reasonable for practical deployments.

The existing LEACH variants have provided notable improvement in terms of energy efficiency and network lifetime for WSNs, they still exhibit several limitations. In LEACH and its centralized version LEACH-C [14], nodes with high energy are chosen clearly based on indecisive or position, leading to uneven loss of energy of nodes resulting in loss of nodes series earlier. E-LEACH [15] enhanced CH selection with intelligent mechanisms yet do not address a multi-criteria all-encompassing perspective, leading to non-optimal energy allocation. LEACH-GA [16], GAO-LEACH [17] and μGA-LEACH [18] used genetic algorithm to optimize CH selection with potentially an increase in computational load, and they cannot completely balance energy consumption in the network. Energy-efficient protocols such as EE-LEACH [20] which used fuzzy logic and S-LEACH that uses sector-based clustering as a node selection strategy, both are efficient in preserving energy but does not incorporate all the aspects of every factor, such as node degree and residual energy. ACHs-LEACH [22] and E-LEACH [23] emphasizes CH selection and data aggregation but may struggle with scalability in large-scale networks. LEACH-XMP [24] introduces a nonlinear energy model but requires complex computations for cluster formation. In contrast, the proposed LEACH-MCDM protocol overcome these limitations by applying MCDM approach for CH selection based on RE, DBS and ND. Ensuring a more balanced energy distribution not only minimizes the prospect of early failure of nodes, but prolongs the life time of the network. Moreover, LEACH-MCDM further reduces communication overhead while optimizing paths for data delivery, presenting it with high efficiency and scalability potential in energy-constrained WSN scenarios.

3. NETWORK MODEL

The network model employed in this work to propose enhancement to the LEACH for a WSNs consists of a number of nodes deployed in the given area. All nodes are endowed with communication facilities, data processing, and sensing that enable the implementation of the algorithms. The communication model depends on the radio energy dissipation model as indicated in the Figure 1; The energy needed in transmitting and receiving messages depends on the distance between the nodes and the size of the message. In this model of energy consumed, the energy used to transmit a message of $L - bit$ over a distance of d can be given by Equation 1. The amount of energy used per bit during the operation of either the transmitter or the reception circuit [14], denoted as E_{elc}, depends on the amplifier model used for the transmitter.

$$E_{Tx}(L,d) = \begin{cases} L \cdot \epsilon_{fs} \cdot d^2 + L \cdot E_{elc} & \text{if } d \leq d_0, \\ L \cdot \epsilon_{mp} \cdot d^4 + L \cdot E_{elc} & \text{if } d > d_0. \end{cases} \tag{1}$$

The energy dissipation model used in this work is based on free-space and multi-path fading which are widely accepted in wireless communication theory [14]. ϵ_{fs} and ϵ_{mp} are two energy amplification factors for the free space model and the multi-path fading model, respectively. The free space model (which holds for short distances ($d \leq d_0$)) assumes signal transmission is achieved in space free of obstacles, wherein the energy required for signal transmission is proportional to d^2. This is consistent with the inverse square law of signal attenuation due to the propagation of the signal wavefront. For distances greater than d_0, we obtain the multi-path fading model, in which the consumed energy is proportional to d^4. This also includes secondary loss from reflections, scattering, and interference in obstructed environments. The distance $d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}}$ gives the transition point between models. In addition, E_{ele} stands for the energy followed by each bit to activate either transmitter or receiver circuits regardless of the transmission distance.

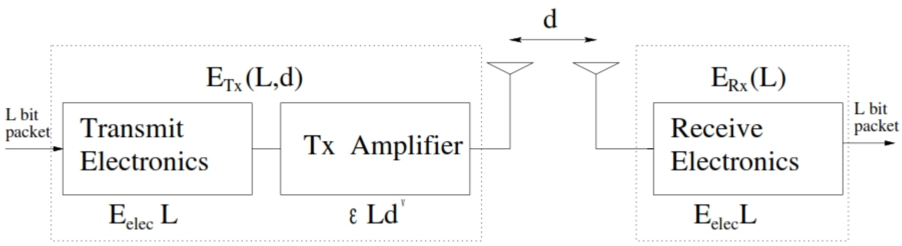

Figure 1. Radio energy dissipation model

The energy consumed by a CH for a particular round is calculated by considering the energy required to receive data from non-CH nodes, process it, and send it to the BS. The total energy dissipation of a CH can be expressed as:

$$E_{CH} = \frac{n}{k} L \cdot E_{DA} + \left(\frac{n}{k} - 1\right) L \cdot E_{elc} + L \cdot \epsilon_{fs} d_{toBS}^2 + L \cdot E_{elc} \tag{2}$$

where n is the total number of nodes, d_{toBS} is the distance from the CH to the BS, k is the number of clusters, and E_{DA} is the energy needed for data aggregation.

For non-CH nodes, the energy consumption for transmitting data to their respective CHs is given by:

$$E_{nonCH} = L \cdot \epsilon_{fs} \cdot d_{toCH}^2 + L \cdot E_{elc} \tag{3}$$

where d_{toCH} is the distance from a sensor node to its associated CH.

This network model ensures that energy consumption is optimized by considering the distances between the BS and the nodes, effectively balancing the load across the network and extending the overall network lifespan.

4. METHODOLOGY

4.1. LEACH Protocol

LEACH [13] is one of the most famous protocol introduced with an aim of reducing energy consumption in WSNs. The core idea of LEACH is the clustering method in which the whole area is splitted into clusters. Every cluster is controlled by an especial node called CH that pools data from other nodes in the cluster of the WSN and transmits it to the BS. This eliminates the energy consumed in every node trying to establish a direct contact with the BS which in turn minimize the energy capacity needed.

The primary innovation of LEACH lies in its approach to CH selection. Rather than having the same node act as the CH for extended periods, which would quickly drain its battery, LEACH rotates the CH role among the nodes to distribute energy usage evenly across the network. In each round, nodes decide whether to become the CH based on a probabilistic algorithm. Every node produces a random number within the range of 0 to 1. If the value is below a threshold $T(n)$, that node will selected as cluster leader for the current round. The threshold is determined as:

$$T(n) = \begin{cases} \frac{P}{1-P\times\left(r \mod \frac{1}{P}\right)} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

where G is the set of nodes that have not been selected as CHs in the last $(\frac{1}{P})$ rounds, r is the current round number, and P is the desired percentage of CHs in the network. Nodes that have already served as CHs in recent rounds are excluded from becoming CHs again until all other nodes have had a chance, ensuring a fair rotation and balanced energy consumption.

Despite its efficiency in reducing energy consumption, LEACH has several limitations. The probabilistic method for CH selection does not consider important factors like the number of neighboring nodes, DBS, or RE. Consequently, nodes with low battery power or nodes that are far from the BS may be chosen as CHs leading to premature unbalanced energy distribution and energy depletion across the network.

The random selection also means that the spatial distribution of the selected CHs are not ideal; certain nodes may be far from their selected CH even though nodes in the network are expected to consume less energy to communicate with nearby nodes. These limitations have necessitated various improvements and adaptations to LEACH including the method presented in this study where CHs are selected using a multi-criteria decision making approach for efficiency and effectiveness in curbing these problems.

4.2. Enhanced LEACH Protocol

The LEACH protocol is widely implemented in WSN, the protocol has some drawbacks mainly arising from the random election of the CH. In the standard LEACH protocol, CHs is randomly elected using probability without considering RE; distance between BS and CH, and the network degree of the node. This results in inefficient operations, where some nodes which have low energy level or that are far from the BS are selected as CHs, thus leading to early exhaustion of energy in the network. Also, some of the CHs may manage many nodes compared to others, which results in congestion and additional ineffectiveness.

To overcome these challenges, the enhanced LEACH protocol introduces a multi-criteria decision-making process for selecting CHs. This enhancement takes into consideration other remnants of energy parameters including RE, DBS, and ND in each node thus making the selection process more proportional and efficient. This has replaced the probability factor used in selecting the CHs with a weighted formula that enhances the best nodes for the task. Algorithm 1 summarizes the proposed LEACH-MCDM protocol.

The proposed formula for CH selection is expressed as:

$$T(n) = \alpha\frac{E_n}{E_{max}} + \beta\frac{d_{max} - d(n)}{d_{max}} + \gamma\frac{k_n}{k_{max}} \tag{5}$$

where α, β, and γ are weighting coefficients of each factor, RE, DBS, and ND, respectively. E_{max} is the maximum energy among all nodes, and E_n is the current RE of node n. K is the ND of node n (i.e., the number of neighboring nodes), and k_{max} is the maximum ND in the network. $d(n)$ is the distance from node n to the BS, and d_{max} is the maximum distance between any node and the BS.

The derivation and justification of this formula are as follows:

1. **Residual Energy (RE):**

Algorithm 1 Enhanced LEACH Protocol using MCDM

Input: Sensor nodes n, maximum energy E_{max}, distance to base station $d(n)$, node degree $k(n)$
Output: Optimal Cluster Head (CH) selection
Initialization: Set initial energy for all nodes, define α, β, and γ coefficients
for each round **do**
  for each node n in the network **do**
    Compute the MCDM-based threshold:
    $T(n) = \alpha \frac{E_n}{E_{max}} + \beta \frac{d_{max} - d(n)}{d_{max}} + \gamma \frac{k(n)}{k_{max}}$
    Generate a random number r between 0 and 1
    if $r \leq T(n)$ and node n is not a CH **then**
      Node n becomes a CH
    end if
  end for
  Form clusters by associating each non-CH node with the nearest CH
  for each cluster **do**
    Perform data aggregation and transmit data to the base station
  end for
  Update residual energy for each node
end for
End Algorithm

- The residual energy of a node, denoted as E_n, is a critical factor in CH selection. Nodes with higher residual energy are better suited to handle the energy-intensive tasks of data aggregation and transmission, ensuring a balanced energy consumption across the network.
- The term E_{max} normalizes the residual energy of node n with respect to the maximum residual energy $\frac{E_n}{E_{max}}$ in the network. This ensures that nodes with sufficient energy have a higher probability of being selected as CHs, reducing the risk of premature energy depletion.

2. **Distance to the Base Station (DBS):**

- The distance between node n and the BS, denoted as $d(n)$, directly impacts the energy required for data transmission. Nodes closer to the BS require less energy to transmit data, making them more energy-efficient choices for CHs.
- The term $\frac{E_n}{E_{max}}$ normalizes the distance, where d_{max} is the maximum distance between any node and the BS. This formulation prioritizes nodes closer to the BS, minimizing the energy cost of transmitting collected data.

3. **Node Degree (ND):**

- The node degree, denoted as k_n, represents the number of neighboring nodes. Nodes with an optimal number of neighbors are preferred for CH selection, as they can form balanced clusters without being overwhelmed by excessive communication tasks.
- The term $\frac{k_n}{k_{max}}$ normalizes the node degree with respect to the maximum node degree k_{max} in the network. This ensures that nodes with too few neighbors (which may lead to inefficient clustering) or too many neighbors (which may cause congestion) are less likely to be selected as CHs.

The three factors are combined into a single weighted formula, where α, β, and γ are the weighting coefficients. These coefficients are chosen such that $\alpha + \beta + \gamma = 1$, and their values can be adjusted based on the specific requirements of the network. The weighted combination ensures that CH selection is optimized for energy efficiency, balanced cluster formation, and reduced communication costs, addressing the limitations of the traditional LEACH protocol.

With the integration of these three factors, LEACH-MCDM protocol can overcome the limitations of the original LEACH where the election of CH was random without regard to network conditions. LEACH-MCDM enhances energy balance since nodes with highest energy and better network conditions are chosen which extends the network lifetime. It also lowers the communication cost by choosing the CHs near the BS and also, by using the node degree factor, it distributes the load of communication evenly to all the selected heads of clusters to avoid over stressing them. Simulation results demonstrate that the enhanced LEACH protocol outperforms the traditional LEACH in terms of network longevity, energy efficiency, and overall performance, making it an ideal solution for energy-constrained WSNs applications.

5. SIMULATION RESULTS

5.1. Evaluation metric and implementation Details

To assess the efficacy of the enhanced LEACH, several key metrics were employed. Network lifetime is a primary metric, measured by the number of operational rounds until the first node dies and the time until all nodes deplete their energy. Energy efficiency is assessed by tracking the energy consumption per round, with a focus on comparing the energy utilization between CHs and non-CHs. Data throughput, representing the total number of packets successfully received by the BS, is also evaluated to measure the effectiveness of communication. Additionally, the balanced energy consumption across nodes and load distribution among CHs are analyzed to determine how well the enhanced protocol manages network resources.

For implementation, the simulation was performed using MATLAB, a common tool for wireless sensor network protocols. A network with a 100 nodes randomly distributed sensor nodes was simulated over a 100×100 m^2 area, with a BS located at the center, where the initial energy levels were set to 0.5 J. The enhanced LEACH was compared against the traditional LEACH, LEACH-C, and LEACH-GA protocols in terms of the aforementioned metrics. Default parameters such as the energy consumption model, radio transmission range, and amplification energy were summarized in Table 1 shows additional simulation parameters. The results indicated that the proposed approach significantly prolongs network longevity and enhances energy efficiency.

Table 1. Simulation parameters.

Parameters	Value
NO. of nodes	100
Network size	100 m^2
r	3000
K	4000
E_0	0.5 J
E_{DA}	5 nJ/bit/message
E_{elc}	50 nJ/bit
ϵ_{mp}	0.0013 pJ/bit/m^4
ϵ_{fs}	10 pJ/bit/m^2
α	0.5
β	0.3
γ	0.2

5.2. Results and discussion

The results demonstrate a significant improvement in network lifetime with the proposed LEACH-MCDM protocol compared to the traditional LEACH, LEACH-C, and LEACH-GA protocols. Specifically, the point at which the First Node Dies (FND), which is a critical metric for assessing energy efficiency and network longevity, shows marked enhancements. For the standard LEACH protocol, the first node dies at round 672, while LEACH-C, which incorporates centralized clustering, extends this threshold to 784 rounds. The LEACH-GA protocol, which leverages genetic algorithms for CH optimization, further increases the FND to 820 rounds. In contrast, the proposed LEACH-MCDM protocol achieves a remarkable FND of 1193 rounds, as presented in Table 2 and Figure 2, this substantial improvement highlights the effectiveness of the multi-criteria selection process in balancing energy consumption, ultimately extending network lifespan. By integrating DBS, RE, and ND into CH selection, LEACH-MCDM optimizes resource allocation, leading to a network that remains operational significantly longer than its predecessors.

Table 2. First Node Death Comparison Between Methods

Method	First node dies
LEACH	672
LEACH-C	784
LEACH-GA	820
LEACH-MCDM	1193

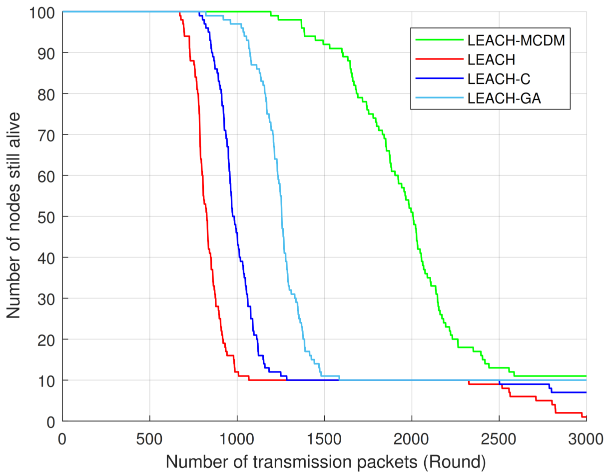

Figure 2. The number of active nodes over 3,000 rounds.

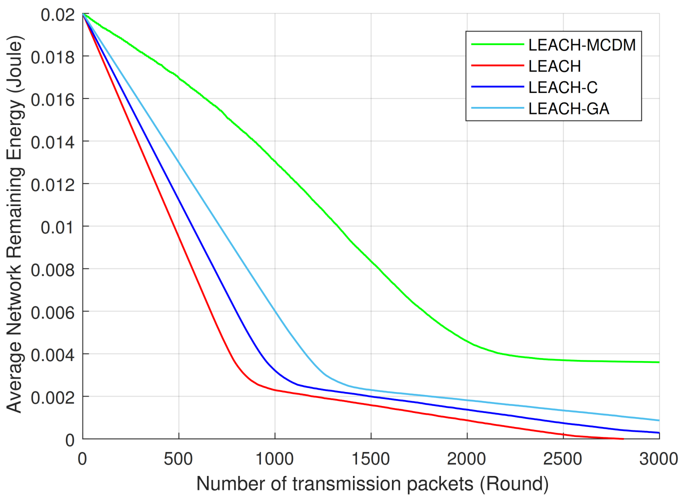

Figure 3. The energy efficiency of all protocols.

The number of living nodes per number of transmission packets (rounds) shown in Figure 3 indicates the energy efficiency and maintenance duration of the network with different protocols. When the energy of the nodes is exhausted, they die, and the rate of node death is dependent on the energy consumption patterns of each protocol. Moreover, LEACH-MCDM effectively aggregates data for efficient routing decisions, significantly reduces communication overhead, and maximizes data transmission paths to minimize energy consumption and ensure longer node lifetimes. LEACH-MCDM uses the MCDM approach by highlighting RE, DBS, and ND. Thus nodes with a larger amount of residual energy and shorter distance to the BS, as well as optimal connectivity are chosen as CHs, resulting in better distribution of energy exhaustion of the network nodes. On the other hand, traditional LEACH is based on random CH selection, which leads to low residual energy nodes or nodes located far from the BS being selected as CH. As a result, this will cause uneven energy depletion and early decay of nodes, which is validated that the alive nodes in LEACH will decrease faster. Similarly, LEACH-C and LEACH-GA show improvements over LEACH but still fall short of LEACH-MCDM due to their less comprehensive CH selection mechanisms. Furthermore, the energy efficiency of LEACH-MCDM is manifested in its data aggregation and routing policies that minimize the communication overhead and provide an optimal path for transmission, which leads to reduced consumption of energy and prolongs the surviving time of the nodes.

Figure 4 illustrated the average remaining energy of the network in respect to the number of transmission packets (rounds) of each protocol. LEACH-MCDM showed a reduced decline in the remaining energy compared to LEACH-C and LEACH-GA, which illustrated its better energy management ability. The slower decline in remaining energy for LEACH-MCDM compared to LEACH-C and LEACH-GA highlights its superior energy management. Which significantly lowers the energy consumption in communication, sensing, and data processing, due to optimized choice of CH and efficient routing strategies implemented in the protocol. In LEACH-MCDM, the CHs are selected based on residual energy, distance to the BS, and node degree so that energy-consuming tasks are covered by nodes with a sufficient energy level and good network conditions. This approach reduces the energy spent on data transmission and aggregation since CHs closer to the BS expend less energy for communication links and nodes with optimal connectivity relieve themselves from excessive data relaying. On the other hand, the traditional LEACH, LEACH-C and LEACH-GA do not take into account such optimization which leads to greater energy consumption and hence faster network energy depletion. The energy efficiency leads to the longer network lifetime as shown in Figure 3, where the number of alive nodes (which represents the number of alive nodes after the run of the simulation) is higher for LEACH-MCDM than for other protocols.

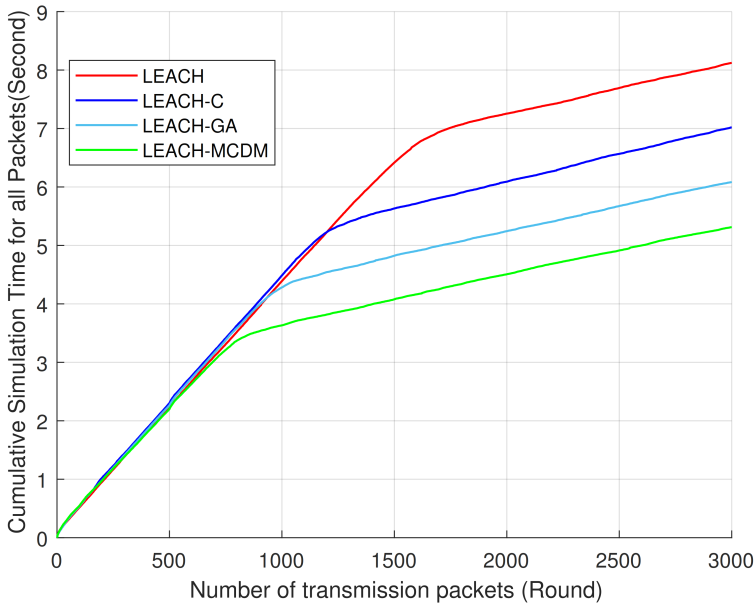

Figure 4. The time consuming of all protocols.

Figure 5 illustrated the cumulative packets transmitted to the BS over rounds, the proposed LEACH-MCDM protocol outperforms all previous protocols, including LEACH, LEACH-C, and LEACH-GA. The results indicate that LEACH-MCDM obtains a much more cumulative packets forwarded to BS. This is primarily due to its MCDM approach for CH selection, which considers RE, DBS, and ND. LEACH-MCDM prolongs node lifetime and improves the efficiency of data transmission over time by ensuring a more balanced energy consumption across the network through prioritizing the nodes with higher residual energy, shorter distances to the BS, and optimal connectivity. In contrast, traditional LEACH has the minimum cumulative packets sent as it randomly chooses the CH in which often results in uneven energy depletion and early node failures. Both LEACH-C and LEACH-GA perform significantly better than LEACH. LEACH-C benefits from CH selection being made centrally rather than in a distributed manner, while LEACH-GA applies a genetic algorithm to optimize performance. However, both protocols still fall short of LEACH-MCDM, since they do not take into account all the pertinent factors in terms of CH selection. The higher cumulative packet transmission in LEACH-MCDM highlights its ability maintain network connectivity and network operation longer than LEACH and other approaches, which results in a more energy-efficient solution for WSNs. This improves throughput and increases network lifetime with the optimum selection of CH which is selected by proposed approach.

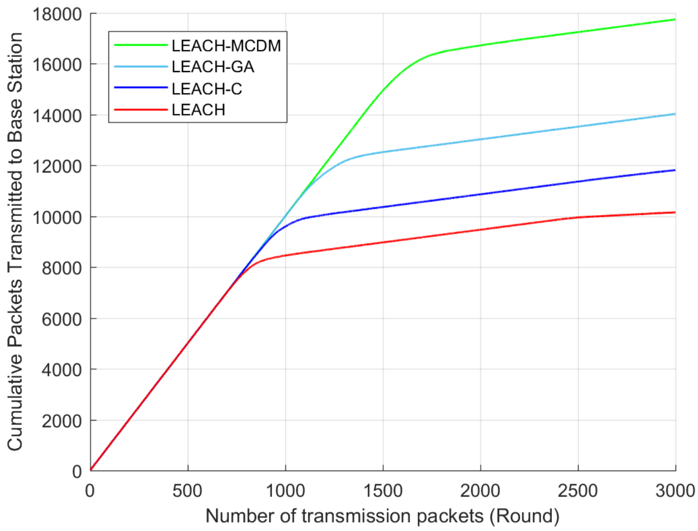

Figure 5. Cumulative Packets Transmitted to Base Station Over Rounds.

6. CONCLUSION

This paper presents an enhanced version of the LEACH protocol, named LEACH-MCDM, designed to improve network longevity and energy efficiency in WSNs. By incorporating Multi-Criteria Decision-Making factors(distance to the base station, node degree, and residual energy), LEACH-MCDM overcomes key limitations of the traditional LEACH protocol. The results demonstrate that LEACH-MCDM significantly extends the time until the first node dies compared to LEACH, LEACH-C, and LEACH-GA, highlighting its effectiveness in maintaining a balanced energy consumption across nodes. Additionally, LEACH-MCDM achieves reduced communication costs and lower simulation time, which contributes to improved data transmission efficiency. Overall, the proposed protocol proves to be a promising solution for energy-constrained WSN applications, enhancing both network longevity and operational performance. Future work could explore further optimizations in CH selection and adaptation to various WSN deployment environments.

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