Optimizing energy efficiency in wireless sensor networks with integration of Calinski-Harabasz index in K-means clusterings

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ABSTRACT

The optimization of energy consumption and the assurance of efficient data transmission are critical factors in enhancing the longevity and performance of wireless sensor networks (WSNs). This study introduces an advanced clustering technique aimed at prolonging the network's lifespan while facilitating reliable data delivery. By integrating the Calinski-Harabasz index into the traditional K-Means clustering approach, the methodology evaluates the quality of clusters and determines the optimal number of clusters, which leads to better node organization within the network. Moreover, the selection of routing pathways from cluster heads to the base station is strategically optimized to conserve energy. Simulation results demonstrate that this novel dual enhancement technique surpasses traditional K-Means in multiple areas, including power consumption, network reliability, and successful data delivery. Consequently, the suggested advancements in cluster formation and routing substantially enhance the performance of energy-limited wireless sensor networks, boosting their robustness and reliability in practical applications.

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1. INTRODUCTION

The applications such as environmental monitoring and healthcare benefit greatly from wireless sensor networks (WSNs). However, the limited lifetime of these networks due to their energy consumption poses a major challenge. Grouping nodes into clusters using algorithms such as K-Means can improve energy efficiency by designating a central cluster head (CH). However, conventional K-Means approaches struggle to form optimal clusters and select the best cluster heads, which limits energy savings [1]-[5].

Unlike previous research that used K-Means to improve network efficiency, our study distinguishes itself by integrating the Calinski-Harabasz index to assess cluster quality [6], [7]. This approach optimizes not only the selection of cluster heads (CHs) but also the formation of the clusters themselves, resulting in more efficient energy utilization and enhanced network stability. Furthermore, optimizing communication paths between CHs and the base station ensures more reliable data transmission while reducing the amount of retransmitted data. This methodology outperforms traditional clustering techniques by providing more efficient energy management and increased overall performance [8]-[11].

The structure of this paper is as follows: section 2 offers a review of relevant studies, while Section 3 provides a description of the presented system. In Section 4, we outline the characteristics of the proposed protocol and its modules. Section 5 focuses on the simulation of the proposed protocol and evaluates its effectiveness. Lastly, the conclusions are drawn in the final section.

2. RELATED WORKS

A considerable amount of research has been dedicated to optimizing routing protocols in wireless sensor networks through the improvement of cluster formation methods, particularly with K-Means. Traditional K-Means clustering improves energy efficiency by grouping sensor nodes and assigning cluster heads (CHs) to facilitate communication with the base station. However, recent advancements have introduced alternative algorithms and optimization strategies to refine these methods further [12]-[16].

For instance, the study in [17] leverages genetic algorithms to reduce redundant CHs by merging neighboring clusters, thereby improving K-Means' initial centroid selection. Similarly, Diakhate *et al.* [18] uses the swarm intelligence algorithm to select the optimal CHs, improving energy efficiency. However, it requires careful tuning of parameters, such as the number of agents used. In [19], an alternative approach, adaptive K-Means, is employed to refine centroid placement, but it still faces challenges with selecting initial centroids and determining the optimal number of clusters.

An enhanced K-Means clustering technique is introduced in [20], in which CH selection relies on various factors. such as leftover energy, closeness to the base station, and the density of nodes, promoting improved energy efficiency. Nonetheless, it is essential to uphold the appropriate equilibrium among these elements for ongoing performance. In the meantime, Panchal and Singh [21] present the EADCR protocol, designed to enhance the efficiency and longevity of WSNs. through the use of a multi-hop routing approach. Although it is effective, its complexity could pose a drawback in resource-limited settings.

An alternative method is described in [22], where the EEHCHR algorithm employs Fuzzy C-Means (FCM), Euclidean distance and remaining energy. Its goal is to reduce energy consumption. It features a hierarchical routing system as well. A hybrid routing algorithm (HRA-NP) is presented [23]. It combines Naïve Bayes with an improved particle swarm optimization (PSO) technique. CHs are selected based on likelihood, followed by employing multi-hop routing. This path is enhanced for the base station utilizing an upgraded PSO model.

3. DESCRIPTION OF SYSTEM

This part offers a detailed summary of the system framework we propose. It starts by detailing the framework of the network, then provides an in-depth examination of the energy usage patterns. Following this, essential definitions and fundamental assumptions are presented to lay the groundwork for the suggested method.

3.1. Architecture overview

Our algorithm is designed for fixed WSNs that include a base station and n stationary sensor nodes positioned in a 2D area. The BS is tasked with collecting data from sensor nodes that are strategically placed to guarantee thorough data acquisition. In the simulation setup, the following assumptions are made: the sensor nodes are deployed randomly and remain stationary after placement; all nodes are identical, having the same initial energy, processing power, and communication capabilities; each node is aware of its location and remaining energy, which aids in selecting CHs and aggregating data; and the base station (BS) is assumed to have unlimited computational power, enabling it to communicate directly with any node as needed.

3.2. Framework for energy efficiency

In this study, we employ the framework for energy efficiency developed in LEACH for WSN [24]-[27]. This model differentiates between two communication scenarios based on the distance between sensor nodes. When the distance surpasses a certain threshold d_0, the multipath fading model is applied, accounting for signal dispersion and interference. Conversely, for distances below d_0, the free-space propagation model is used, assuming an unobstructed environment. The threshold d_0 is computed using a predefined in (1), enabling an adaptive selection of the most efficient transmission model to optimize energy usage.

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \quad (1)$$

where $\mathcal{E}_{fs}$ and $\mathcal{E}_{mp}$ defines the model for transmitter amplifier parameters.
E_{tx} : power required by a node to send information to another node at a distance d is expressed as:

$$E_{tx} = \begin{cases} mE_{elec} + m\mathcal{E}_{fs}d^2 & , d < d_0 \\ mE_{elec} + m\mathcal{E}_{mp}d^4 & , d \geq d_0 \end{cases} \quad (2)$$

where E_{elec} represents the power required of a node for transmitting/receiving an information, where m is bits of data.

The power consumed by a sensor to capture information is independent of the distance d between the transmitting and receiving nodes, as shown in equation (3):

$$E_{rx} = mE_{elec} \quad (3)$$

4. PROTOCOL PROPOSED

The algorithm we propose is composed of three key phases: cluster formation, cluster leader selection, and data aggregation and transmission. Each phase is key to making nodes in the network work better. They group nodes, manage energy use, and combine data for sending. Communication is improved through strong intranode and internode connections. This leads to data being sent to BS. The proposed methodology is depicted in the block diagram shown in Figure 1.

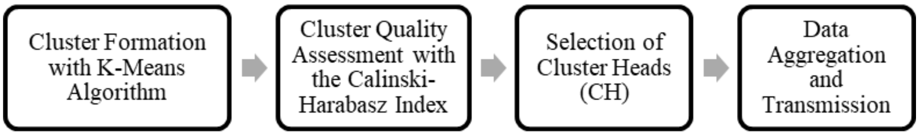

Figure 1. The block diagram of our proposed protocol

4.1. Cluster Formation

The process of cluster formation is a crucial step in enhancing power efficiency within WSNs. This will be accomplished using methods such as the K-Means algorithm, the Calinski-Harabasz Index, and the residual energy of nodes [28], [29]. This approach allows for the creation of clusters. These clusters not only minimize distances between clusters, but also ensure a more equitable distribution of energy loads, thus extending the network's lifespan.

In the first step, our algorithm selects K centroids, where C_i refers to the centroid of cluster i. These centroids are then represented by:

$$C_i = \{c_1, c_2, \dots\dots, c_K\} \quad (4)$$

Nodes join their clusters based on the nearest centroid using the following:

$$Cluster(n) = arg_i/min\left(\frac{\|n - c_i\|^2}{E_{res}(n)}\right) \quad (5)$$

where $\|n - c_i\|$ is separation between node n and c_i, with $E_{res}(n)$ referring to the remaining energy of sensor n. The centroid update is presented in the following formula, where Si refers to the set of nodes in the cluster i:

$$c_i = \frac{\sum_{n \in S_i} n \times E_{residual}(n)}{\sum_{n \in S_i} E_{residual}(n)} \quad (6)$$

To evaluate clustering quality, our algorithm uses the Calinski-Harabasz Index (CHI), which measures the separation between clusters and the compactness within clusters during the cluster formation process. First, we determine the variance to evaluate the level of compactness within the clusters (7).

$$SSE = \sum_{k=1}^{K} \sum_{i \in S_k} E_i \, . \, (\|p_i - c_k\|^2) \, , p_i = (x_i, y_i) \quad (7)$$

Next, we compute the inter-cluster variance by calculating the distance between the cluster centroids and the global centroid of the sensors (8).

$$C_{global} = \left(\frac{\sum_{i=1}^{N} E_i \cdot x_i}{\sum_{i=1}^{N} E_i}, \frac{\sum_{i=1}^{N} E_i \cdot y_i}{\sum_{i=1}^{N} E_i}\right) \quad (8)$$
$$SBC = \sum_{k=1}^{K} (\sum_{i \in S_k} E_i \cdot \|c_k - c_{global}\|^2)$$

The formula for the CHI is provided as (9):

$$CHI = \frac{\frac{SBC}{K-1}}{\frac{SSE}{N-K}} \quad (9)$$

To improve cluster formation, we experimented with various values of k and selected the one that yielded the highest Calinski-Harabasz index. This approach was embedded in a K-means clustering algorithm, where we incorporated the residual energy of nodes in the computation of centroids. By factoring in the residual energy and using the Calinski-Harabasz index for cluster evaluation, we achieved more evenly distributed and energy-efficient clusters within our sensor network.

4.2. Selection of cluster head

In this paper, we present an effective approach for selecting CHs to optimize the energy efficiency of WSNs. This method calculates a score for each node using the following (10).

$$F_i = \frac{E_{residual}(i)}{E_{initial}} + \frac{1}{d_{i,avg}} + \frac{1}{d_{i,BS}} \quad (10)$$

Where the average distance is determined by formula (11)

$$d_{i,avg} = \frac{1}{|S_i|} \sum_{j \in S_i} d(i,j) \quad (11)$$

Once the score is calculated, the node with the maximum score is chosen as the CH:

$$CH = \arg max_{i \in S_i} F_i \quad (12)$$

This method enables dynamic cluster head selection, accounting for the remaining energy, sensor proximity, and the distance to the base station, thus promoting energy balance and enhancing the longevity of the network.

4.3. Data aggregation and transmission

Once the CHs are selected, data transmission to the base station becomes possible. Communication between nodes in a cluster and their respective CHs is handled by time division multiple access (TDMA), where each cluster relies on the residual energy, the distance between neighboring CH nodes and the base station, and the number of neighboring CHs to transfer this data on specific time slots [30], [31].

Several routes are available between CHs and the base station via multi-hop communication. Each CH calculates a weight of each neighboring CH using (14), the neighboring CH with the lowest weight is chosen as an intermediary for transmitting data from the cluster to the base station.

$$C_{ij} = \frac{1}{E_j} + \frac{1}{N_j} + d(j,BS) \quad d(i,BS) > d(j,BS) \quad (14)$$

By leveraging this method of selecting intermediate CHs for multi-hop communication, this strategy ensures better network lifetime as well as increased overall efficiency.

5. EVALUATION AND RESULTS

The following section focuses on the simulation of our proposed protocol as well as other protocols, such as EADCR [21], EEHCHR [22], and HRA NP [23], using the NS2 simulation software. Table 1 shows the simulation parameters.

Table 1. Simulation parameter

Parameter	Value
Network area	200 x 200
Number of nodes	400
Maximum number of rounds	5000
Probability of a node to become a CH	0.1
BS location	200 x 200
Energy dissipation per bit E_{elec}	50 nJ/bit
Energy dissipation for free space $\mathcal{E}_{fs}$	10 pJ/bit/m2
Energy dissipation for multipath delay $\mathcal{E}_{mp}$	0.0013 pJ/bit/m2
Energy dissipation per bit E_{rx}	50 nJ/bit
Data packet size	500 bytes
Simulation time	600s

The evaluation of these protocols is based on key performance criteria, such as energy consumption, network lifetime, and packet delivery rate, which are commonly used to evaluate and compare routing algorithms in wireless sensor networks. To assess cluster quality, we used an improved K-means clustering algorithm based on the Calinski-Harabasz index. This index allowed us to determine that 8 clusters offered the best distribution and utilization of resources in a simulation with 400 nodes. The result is shown in Figure 2.

The simulation results presented in Figures 3 and 4 demonstrate that our algorithm outperforms EADCR, HRA, NP, and EEHCHR according to the indicated performance criteria. One of the main strengths of our approach lies in its ability to accurately determine the optimal number of clusters, allowing efficient distribution of resources across the network. Moreover, our algorithm uses robust criteria to select cluster heads, taking into account both the characteristics of the nodes and their position in the network. As illustrated in Figure 3, our proposed method shows 20% lower energy consumption than EADCR and 15% lower energy consumption than EEHCHR throughout the simulation period, highlighting its superior energy efficiency.

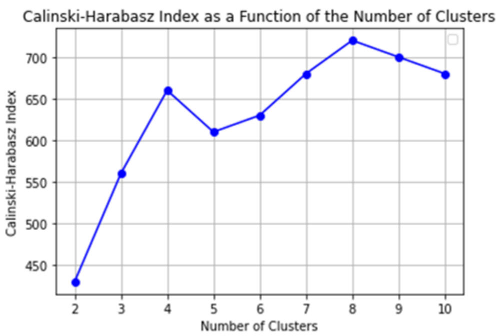

Figure 2. Calinski-Harabasz index

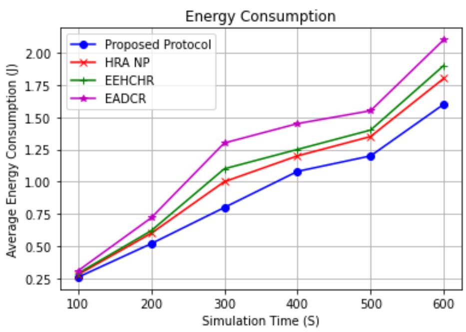

Figure 3. Average energy consumption

Figure 4 illustrates the performance metrics obtained during the experimental evaluation. These results highlight the effectiveness and relevance of our proposed protocol. As illustrated in Figure 4(a), the proposed protocol demonstrates an impressive packet delivery rate of up to 95%, maintaining high performance even as network density increases. In contrast, the performance of the EADCR protocol declines significantly to approximately 80% as node density rises. Both HRA NP and EEHCHR exhibit moderate packet delivery rates around 85%, with a noticeable decrease in performance at higher node densities. These findings underscore the critical role of optimized cluster head selection and efficient cluster management in ensuring reliable data transmission across the network.

Figure 4(b) illustrates that our protocol provides the best management of active nodes, outperforming the studied protocols in terms of maintaining node activity. HRA NP experiences a drop, with fewer than 300 nodes remaining after 250 seconds, a drop of approximately 25%. In comparison, EEHCHR and EADCR show even more pronounced drops of 40% and 50%, respectively. These results highlight the superior efficiency of our protocol in managing network resources, making it particularly suitable for applications requiring sustained network activity.

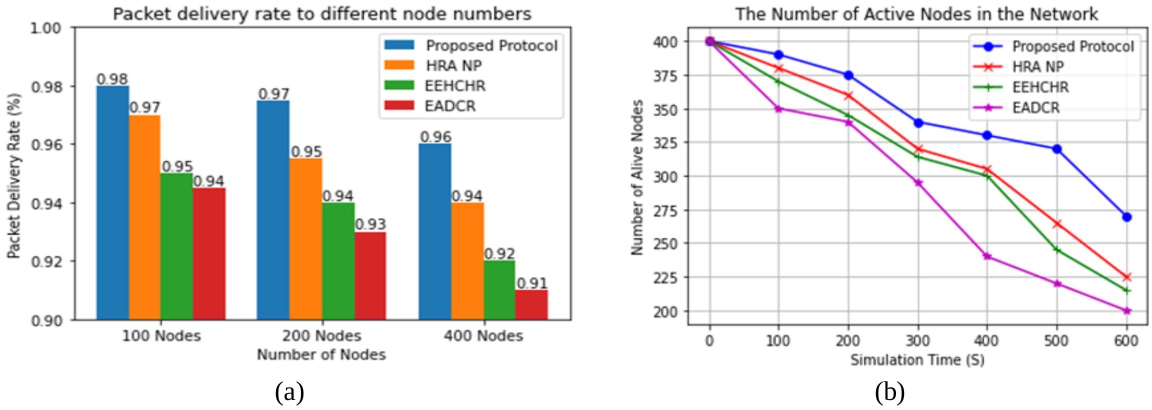

Figure 4. Performance metrics; (a) packet delivery rate and (b) number of alive nodes

Unlike previous research, our work introduces the Calinski-Harabasz Index to evaluate cluster quality, offering a novel approach to enhance cluster formation and relay node selection. While earlier studies concentrated on optimizing routing protocols, our method adds a fresh perspective by considering these additional factors. However, a significant limitation of our simulations is that they were performed in a controlled environment. This means that real-world conditions, such as fluctuations in the network environment and unpredictable node behaviors, were not considered. Furthermore, some unexpected results, including superior packet delivery performance in low-power scenarios, suggest that further exploration is needed. This could include analyzing factors not considered in our current simulations and validating the results in more varied and realistic environments.

6. CONCLUSION

In conclusion, this study has highlighted the importance of integrating the Calinski-Harabasz index into the K-Means clustering process to optimize energy in wireless sensor networks. Our simulations show that this approach not only improves energy efficiency but also extends the lifetime of the networks, making monitoring applications significantly more viable. Our results confirm the hypothesis that better cluster evaluation leads to reduced energy consumption. This finding is in line with previous works that highlight the importance of good energy resource management in WSNs. The results pave the way for further research. In the future, it would be relevant to explore the integration of machine learning methods to optimize the selection of cluster heads in real time. This can potentially further improve the energy efficiency and robustness of the networks.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Abderrahim Maizate				✓				✓				✓		
Siham Aouad	✓		✓				✓			✓	✓		✓	
Fiuad Ayoub					✓				✓					✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

Research did not involve humans or animals. Therefore, no ethical approval by an institutional review board was required.

DATA AVAILABILITY

Derived data supporting the results of this study are available upon request from the corresponding author.

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