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Integration of K-Means and Silhouette score for energy efficiency of wireless sensor networks

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ABSTRACT

In wireless sensor networks (WSNs), optimizing energy consumption, and ensuring efficient data transmission are crucial for network longevity and performance. This paper introduces an enhanced clustering technique for WSNs that aims to extend network lifetime and ensure reliable data delivery. Instead of regular K-Means clustering, we integrate the Silhouette score method to evaluate cluster quality and decide the optimal number of clusters. This improves how nodes are grouped together in the network. Additionally, we strategically select routing paths from cluster heads to the base station that minimize energy drainage. Comprehensive simulations show our dual optimization approach outperforms standard K-Means in terms of energy efficiency, stable network organization and effective data transmission and overall, the proposed improvements to clustering and routing significantly advance energy-constrained WSNs toward more sustainable and dependable real-world applications.

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1. INTRODUCTION

Wireless sensor networks (WSNs) have a big impact on many new applications, like keeping an eye on the environment, healthcare, and making factories run better. These networks link up sensors that gather data and send it to a main station. But managing power is still a tough problem, since sensors often run on batteries that don't last long. The latest research shows that people have tried different ways to make WSNs use less energy such as grouping sensors together and finding better ways to send data. Even with these steps forward many systems still don't last as long as they should or work as well as we'd like [1]–[5].

The main issue revolves around the need to cut down on energy use while keeping data moving. Old-school grouping methods, while helpful often can not spread the energy load among nodes. This can cause some sensors to fail too soon and make the network work. So, it's crucial to come up with new ideas to tackle these problems [6]–[9].

Given this situation, our research puts forward a fresh approach. It combines a fine-tuned grouping method based on K-Means and Silhouette score paired with a better way to route data. This method aims to form sensor clusters more efficiently, while minimizing energy consumption during data transmissions. By demonstrating the effectiveness of our approach through simulations, we highlight the significant benefits in terms of durability and performance of WSNs.

The organization of the document is described as follows: section 2 discusses related work and provides essential background information relevant to this study. In section 3, we outline underlining approach of the proposed system. In this section 4, we present various features of the specified protocol, which includes its parts as well. Finally, in the last section 5, we provide the analysis of the simulation of the proposed protocol and its efficiency. In the last part, the conclusion of the research is made.

2. RELATED WORKS

A number of studies have been conducted in order to optimize routing protocols in WSNs by using the K-Means algorithm. Traditional K-Means clustering has made it possible to improve energy efficiency by separating sensor nodes into clusters each with a cluster head (CH) that facilitates communication with the base station (BS). However, there has recently been an attempt to make this approach even more optimal by mixing additional algorithms and metrics [10]–[14].

Kadim *et al.* [15] proposes to reduce the number of redundant CHs in WSNs by replacing two neighboring CHs with a single one, using genetic algorithms. It utilizes the K-Means algorithm to group sensors around CHs and enhance the selection of initial centroids. Diakhate *et al.* [16] use the firefly algorithm to optimize CH selection in WSNs, improving energy efficiency. This method requires fine tuning of parameters, such as the number of fireflies. The study [17] uses min-max k-means to improve centroid selection, with limitations related to the initial centroid selection and the definition of the number of clusters K.

Mwangi *et al.* [18] proposes a CH selection algorithm based on an extended K-Means approach to improve the energy efficiency of WSNs. It chooses nodes close to the centroids based on the remaining power, distance to the BS, and node density. This precise calibration is crucial to avoid compromising performance. Panchal and Singh [19] proposed the energy aware distance-based CH selection and routing (EADCR) protocol to improve the efficiency and lifetime of WSNs by reducing energy consumption through a unique clustering approach and a multi-hop routing strategy. However, the increased complexity of the protocol may pose challenges in resource-constrained environments. Panchal and Singh [20] presents the energy efficient hybrid clustering and hierarchical routing (EEHCHR) algorithm, which uses Euclidean distance, fuzzy c-means (FCM), and residual energy to optimize energy consumption, with a hierarchical routing strategy to improve energy efficiency.

Wang *et al.* [21] proposed a hybrid routing algorithm based on Naïve Bayes and improved particle swarm optimization algorithms (HRA NP). CHs are selected based on the conditional probability CH, which is estimated by the Naïve Bayes classifier. After the selection of CHs, the multi-hop routing algorithm is applied to the CHs. The best routing path from each CH to the BS is obtained from an improved particle swarm optimization (PSO) algorithm.

3. SYSTEM OVERVIEW

This section provides a detailed description of our proposed system model. It starts with an introduction to the network model, followed by an explanation of the energy consumption model. Afterward, several definitions and hypotheses are outlined.

3.1. Network model

Our algorithm is designed for static networks comprising a BS and n fixed sensors. We assume that the WSN is in a two-dimensional plane. A BS collects data from n sensors, which are randomly scattered to collect information.

For the network simulation, we make the following assumptions: nodes are randomly scattered in a two-dimensional plane and remain stationary after deployment; all sensor nodes in the monitoring area are homogeneous, with equal initial energy and identical processing and communication capabilities; sensor nodes are aware of their position within the network and their residual energy, and can designate CHs to merge duplicate data; and the BS has unlimited computing energy and capacity, enabling direct communication from each node.

3.2. Energy consumption model

Our paper uses the energy model defined in low energy adaptive clustering hierarchy (LEACH) for WSNs [22]–[26]. This model distinguishes two cases depending on the communication distance between the nodes. If this distance exceeds a threshold d_0, the multipath decay channel model is used, which considers the effects of signal reflection and diffusion. On the other hand, if the communication distance is less than d_0, the free space channel model is applied, considering an environment without obstacles. The threshold d_0 is determined by a specific (1), allowing dynamically choosing the most appropriate model to minimize energy consumption:

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

where ε_{fs} and ε_{mp} represents the transmitter amplifier parameters model.

E_{tx} is the energy consumption of a sensor for transmitting m bits of data to another sensor located at a d is given by:

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

where E_{elec} represents the energy needed by a sensor to transmit or receive a packet, and d is the separation between the transmitting and receiving sensors.

The energy used by a node to receive mmm bits of data does not depend on the distance d between the transmitting and receiving nodes. This can be represented by (3):

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

this equation indicates that the energy consumption for receiving data is directly proportional to the number of bits received and does not depend on the distance *d* between the nodes.

4. PROTOCOL PROPOSED

Our proposed protocol consists of three main phases: the formation of clusters, the selection of cluster leaders, and the aggregation and transmission of data. Most of these phases contribute towards improving the efficiency of nodes within a network by creating clusters of nodes, controlling energy consumption, and effectively combining data for transmission. Communications are facilitated through efficient intranode and internode connections and finally sending the data to the BS.

4.1. The cluster formation

Cluster formation is a crucial step in optimizing the energy efficiency of WSNs. This cluster formation will be achieved employing aspects such as K-Means algorithm, Silhouette score, and residual energy of nodes [27], [28]. This approach lets creating clusters in a way that not only minimizes intra-cluster distances but also considers a more equal distribution of the energy loads which will further increase the network lifetime.

Our algorithm starts by initializing K centroids using the K-Means++ method. The centroids can be represented by:

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

where C_i is the centroid of the i i-th cluster.

Each node is assigned to the cluster with the closest centroid, using a distance weighted by the residual energy. For a node n, the assignment is defined by:

$$Cluster(n) = argmin_i \left(\frac{\|n - c_i\|^2}{E_{residual}(n)}\right) \quad (5)$$

where $\|n - c_i\|$ is the distance between sensor n and centroid c_i, and $E_{residual}(n)$ is the residual energy of node n.

The centroids are updated by calculating the weighted average of the node positions, where the weighting is based on the residual energy of the nodes:

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

where $S\ i$ is the set of sensors in the i i-th cluster.

Our algorithm uses the Silhouette score technique to evaluate the quality of sensor node clustering. For each node i, the Silhouette score s(i) is calculated as (7):

$$s(i) = \frac{b(i)-a(i)}{max\{a(i),b(i)\}} \quad (7)$$

where, $a(i)$ is the energy-weighted average distance between node i and all other nodes in the same cluster:

$$a(i) = \frac{1}{|S_i|-1} \sum_{j \in S_i, j\neq i} \frac{\|i-j\|}{E_{residual}(j)} \quad (8)$$

$b(i)$ is the energy-weighted average distance between node i and all nodes in the nearest cluster to which i does not belong:

$$b(i) = min_{k\neq Cluster(i)}(\frac{1}{|S_k|}\sum_{j \in S_i} \frac{\|i-j\|}{E_{residual}(j)}) \quad (9)$$

the number of clusters K with the highest average Silhouette score is usually chosen as the optimal number of clusters. The final clusters are those that maximize the overall average Silhouette score of the network, weighted by the remaining energy:

$$S = \frac{1}{N}\sum_{i=1}^{N} s(i) \quad (10)$$

where, N is the total sensors in the WSN.

4.2. The cluster head selection

Our paper proposes an efficient method to select CHs in order to optimize the energy efficiency of WSNs. To select a CH, three criteria are taken into account, the residual energy of the node, the average distance between the candidate node and the other nodes of the cluster and also the distance of the node to the BS. This method allows to calculate a score for each node using a fitness function that combines these 3 criteria (11):

$$F_i = \frac{E_{residual}(i)}{E_{initial}} + \frac{1}{d_{i,avg}} + \frac{1}{d_{i,BS}} \quad (11)$$

where, $E_{residual}(i)$ is the residual energy of node i. $E_{initial}$ is the initial energy of the node (used to normalize the residual energy). $d_{i,avg}$ is the mean distance between sensor i and the other sensors in its cluster. $d_{i,BS}$ is the distance of node i i to the BS.

The average distance between node i and the other nodes in its cluster S_i is calculated as (12):

$$d_{i,avg} = \frac{1}{|S_i|}\sum_{j\in S_i} d(i,j) \quad (12)$$

once the fitness functions are calculated for all sensors in a cluster, the node with the maximum fitness magnitude is selected as the CH:

$$CH = \arg max_{i\in S_i} F_i \quad (13)$$

by employing this method, we can dynamically select CHs while considering the remaining energy, the proximity of the sensors, and the distance to the BS, which enhances energy balance and extends the network's lifespan.

4.3. Data aggregation and transmission

Data transmission to the BS is possible after the proper choice of the CHs is made. Inter-cluster communication with the nodes in the cluster and corresponding CHs is, however, done in time division multiple access (TDMA) which assigns specific time-slots to each cluster. For efficient transfer of data in between different clusters of nodes to prolong the energy of the nodes, a multi-hop communication technique has been devised considering the residual energy and distance among neighboring CH nodes and the BS and also the number of neighbors of CHs [28], [29].

There are multiple routes between CHs and the BS through inter-cluster multi-hop communication utilizing relay nodes. Each CH shares information with its neighboring nodes regarding the residual energy E_i of node i, Number of neighbors N_i of node i and distance to the BS $d(i,BS)$. Once this information is received and updated, each CH_i calculates the weight C_{ij} of each of its neighbor CH_j using (14):

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

each CH selects its optimal path to the BS by choosing the CH with the minimum weight as the relay node to the BS.

This strategy guarantees the optimal choice of the next relay node by considering the residual energy, the number of neighboring nodes, and the distance to the BS, applicable to both single-hop and multi-hop communication. This enhances both the network's longevity and its overall performance.

5. SIMULATION AND ANALYSIS

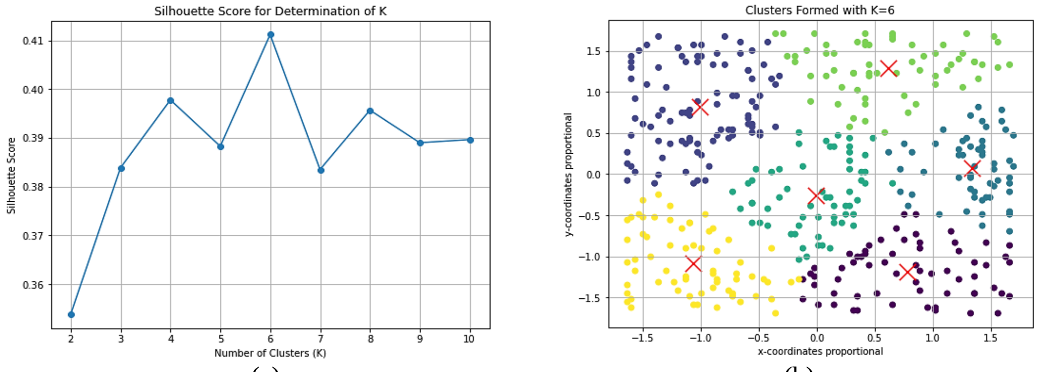
In this part, we will conduct a simulation of our proposed protocol and present the findings. The simulation was performed using the NS2 network simulation software and compared with the EADCR [19], EEHCHR [20], and HRA NP [21] protocols. The evaluation concentrated on essential performance metrics, including energy consumption, network lifetime, and packet delivery rate, which are standard criteria for assessing and comparing routing algorithms in WSNs. To ensure a fair comparison and achieve accurate results, all protocols were tested under the same conditions, as outlined in Table 1.

Our method employs an algorithm derived from the K-Means algorithm, accompanied by the Silhouette score to evaluate the quality of the formed clusters. The Silhouette score, which measures the cohesion and separation of clusters, allowed us to determine the optimal number of clusters by maximizing this score. In our simulation environment comprising 400 nodes, this approach allowed us to identify an optimal number of 6 clusters, thus ensuring an efficient distribution of nodes and optimization of network resources. Figure 1 shows the result obtained.

Figure 1(a) shows the evolution of the Silhouette score as a function of the number of clusters (K). The Silhouette score reaches its maximum at K=6, this peak indicates the best compromise between internal cohesion and separation between clusters. On the other hand, Figure 1(b) presents a cloud of sensor nodes distributed in six distinct clusters according to the result of the Silhouette score obtained k=6.

Table 1. Parameters of the simulation

Settings	Magnitude
WSN zone	200×200
Total of sensors	400
BS coordinates	200×200
Initial energy per sensor node	2 j
Size of data packet	500 bytes
Duration of simulation	600 s
Communication radius for each sensor node	30 m
Maximum iterations for Silhouette score calculation	300



(a) (b)

Figure 1. Silhouette score for determination of k clusters for (a) Silhouette score and (b) clusters formed with k=6

Simulation results of our algorithm, Figures 2 and 3, indicate that it outperforms EADCR, HRA NP, and EEHCHR, particularly in terms of energy consumption, number of active nodes, and packet delivery rate. Our algorithm is distinguished by its ability to optimally determine the number of clusters needed, which allows for efficient resource allocation in the network. It also uses robust criteria to select CHs, taking into account the characteristics of the nodes and their position in the network.

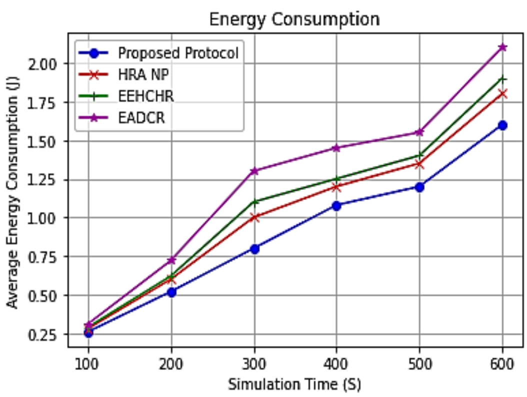
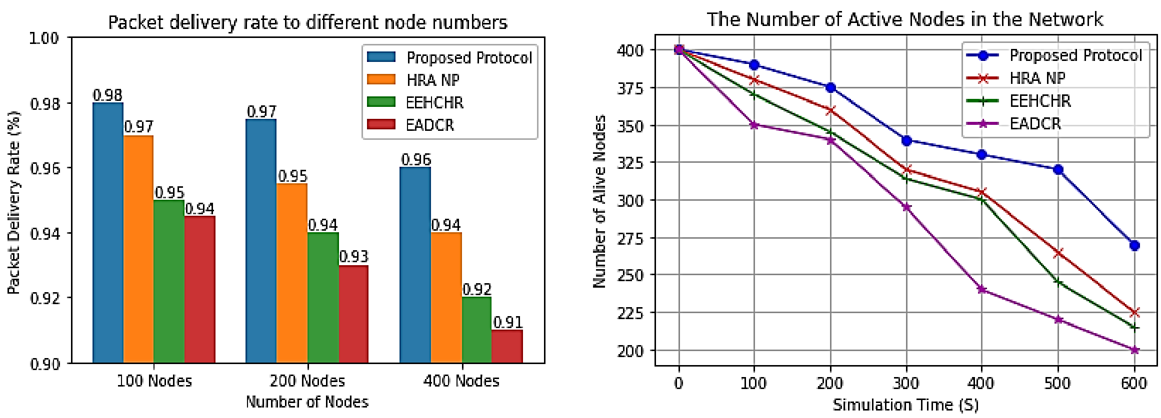


Figure 2. Average energy consumption

Figure 2 demonstrates that the proposed protocol consistently consumes less energy compared to HRA NP, EEHCHR, and EADCR throughout the simulation. Notably, the energy efficiency of the proposed protocol remains superior, particularly at the 600-second mark, indicating its potential for extending network lifetime. In contrast, EADCR shows the highest energy consumption, making it less efficient for energy management.

Figure 3(a) shows that the proposed protocol consistently achieves the highest packet delivery rates across different node densities, thus maintaining efficiency even in the densest networks. In contrast, EADCR exhibits the lowest performance, especially with more nodes. HRA NP and EEHCHR have moderate performance but still decline as the node density increases. The results indicate that our approach not only optimizes energy consumption but also improves the packet delivery rate, ensuring reliable data transmission. This highlights the importance of judicious selection of CH nodes and efficient cluster management, which are key elements of our method.

Figure 3(b) shows that the proposed protocol maintains the highest number of active nodes throughout the simulation, outperforming HRA NP, EEHCHR, and EADCR. HRA NP follows but drops below 300 nodes after 250 seconds, while EEHCHR and EADCR show significantly lower active node counts. This suggests the proposed protocol is most efficient in resource management, making it ideal for applications requiring sustained network activity. This is due to the quality of cluster formation established by our proposed protocol.



(a) (b)

Figure 3. Performance metrics for (a) packet delivery rate and (b) number of alive nodes

Comparing our results with previous studies, we find that while previous works have also explored routing protocol optimization, few have integrated cluster quality assessment methods such as Silhouette score. This is a strength of our study, as it allows for better cluster formation and more efficient relay node selection. However, a limitation of our research is that the simulations were performed in a controlled environment, which may not reflect all the complexities of real-world deployments. Moreover, some unexpected results, such as improved packet delivery rate under low energy conditions, deserve to be explored further.

6. CONCLUSION

This study demonstrated the effectiveness of an innovative approach to improve the energy efficiency of WSNs. By integrating an optimized clustering algorithm based on K-Means and Silhouette score, we successfully formed sensor groups in a more judicious manner, which reduced the energy consumption during data transmission. The simulations performed revealed that our method outperforms traditional techniques in terms of network durability and stability. These results highlight the importance of efficient energy management in WSNs, paving the way for more sustainable and reliable applications in various fields. The advances presented here not only contribute to extending the lifetime of sensors, but also to ensuring continuous and reliable data transmission, which will delight researchers and practitioners in the field.

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