Providing A Novel Distributed Method For Energy Management In Wireless Sensor Networks Based On The Node Importance Criteria

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Abstract

Energy management in wireless sensor networks has great importance. In these networks, sensor nodes typically operate on batteries and due to limited energy resources, energy management is crucial for optimal performance and battery lifetime of these nodes. The use of suitable energy management algorithms in wireless sensor networks can help improve network efficiency and increase the battery life of sensor nodes. In this paper, a new method is proposed for optimal energy consumption management in wireless sensor networks. In the proposed method, each node selects a cluster for itself in a distributed manner or chooses itself as the cluster head. This method is designed based on the importance of nodes. The proposed method was implemented in different scenarios for wireless sensor networks such as sparse and dense wireless sensor networks. In all simulations, the proposed method demonstrated good capabilities in optimal energy consumption management.

Keywords: Energy management, Wireless sensor network, Node importance, power consumption.

1. Introduction

Wireless sensor networks have gained significant importance in a wide range of applications over the past decade. These networks utilize sensor nodes to monitor the environment, and the collected data is transmitted to the cluster head or directly to the sink node. Wireless sensor networks have diverse applications such as military and defense industries, environmental monitoring, and healthcare systems. They operate automatically in hazardous environments such as volcanoes (Alsharafat et al. 2022; Sharma and Gupta 2020).

The performance of sensor nodes is limited by constraints such as processing power, memory, and battery capacity. When sensor nodes consume energy inefficiently, the network lifetime decreases. Therefore, the components of sensor nodes and network management protocols should be designed to increase the network lifetime with reduced energy consumption (Thiyagarajan and Shanmugasundaram 2022; Ordouei et al. 2023; Ordouei and BaniRostam 2018).

Designing energy-efficient routing algorithms for wireless sensor networks to improve their lifetime using the advantages of clustering, data aggregation or data fusion, and techniques such as cluster head selection is crucial. The distributed and clustering-based routing protocol LEACH is the primary example of this category of protocols (Alsharafat et al. 2022).

The following of this article is organized as follows: Section 2 includes a review of related work. Section 3 presents the proposed methods. Section 4 discusses the proposed methods, which have been subjected to numerous experiments. Finally, section 5 provides a conclusion.

2. Related works

Numerous routing protocols have been proposed for wireless sensor networks, and the primary factors in evaluating and distinguishing these protocols are their effectiveness in data retrieval, reduction in resource consumption, and ability to maximize network life time.

The Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol is the main energy-efficient routing protocol among cluster-based routing protocols. It introduced clustering as a cost-effective energy management technique for wireless sensor networks. The protocol uses a randomized rotation of Cluster Heads to distribute the high-energy consumption incurred during communication between wireless sensor networks and sink node to all sensor nodes in the network(Heinzelman, Chandrakasan, and Balakrishnan 2000; Tyagi and Kumar 2013; Arora, Sharma, and Sachdeva 2016; Xu and Gao 2011; Mahapatra and Yadav 2015).

In the LEACH protocol, nodes are randomly divided into several clusters, and each cluster selects a node as its cluster head. These cluster heads then transmit the collected data from nodes within their cluster to the sink. Since data transmission is performed by a smaller number of cluster heads compared to the total number of nodes in the network, energy consumption in the network is significantly reduced. Additionally, in this protocol, nodes periodically work to select a new cluster head, which results in better distribution of energy consumption in the network(Heinzelman, Chandrakasan, and Balakrishnan 2000).

LEACH is a complete distributed routing protocol that does not require global information. The concept of clustering used by the LEACH protocol reduces communication between sensor nodes and the sink, which increases the network lifetime. Additionally, the use of data aggregation techniques by the cluster head reduces the amount of energy consumption for locally correlated data. Allocation of time division multiple access schedules to member nodes allows them to go into sleep mode, preventing intra-cluster collisions and enhancing the battery lifetime of sensor nodes. In the LEACH protocol, every sensor node has an equal opportunity to become a cluster head or a member node during its lifetime, which improves the network lifetime(Singh, Kumar, and Singh 2017).

LEACH protocol has some disadvantages, which can affect the lifetime of the network. One such issue is that the cluster head is randomly chosen in each round, and if a sensor node with low energy is selected, it can result in decreased network lifetime. Additionally, LEACH does not guarantee a fixed number or position of cluster heads, leading to an uneven distribution of clusters in the network and higher energy dissipation. Lastly, the use of single hop communication between the cluster head and the base station in LEACH results in uneven energy dissipation in areas far from the base station, ultimately reducing the lifetime of the sensor network(Singh, Kumar, and Singh 2017).

There are various types of LEACH protocol such as LEACH-Centralized (Heinzelman, Chandrakasan, and Balakrishnan 2002), LEACH-Deterministic Cluster Head Selection(Handy, Haase, and Timmermann 2002), Solar Aware-LEACH(Voigt et al. 2004), Security based LEACH(Ferreira et al. 2005), Fault Tolerance LEACH(Chouikhi et al. 2015), Intra-Balanced LEACH(Salim, Osamy, and Khedr 2014), Cognitive LEACH(Eletreby, Elsayed, and Khairy 2014).

One of the categories of methods for optimizing the lifetime of wireless sensor networks is population-based optimization techniques. These algorithms are inspired by nature or bio-mimicry. Choosing suitable bio-inspired or metaheuristic algorithms that propose the best solution for each problem is crucial. Therefore, no single algorithm can provide the best solutions for all problems; instead, there are several optimization algorithms such as Ant Colony Optimization(Adnan et al. 2013), Genetic Algorithm(Singh and

Sharma 2014), and Particle Swarm Optimization(Gandomi et al. 2013; Ordouei and Namdar 2018).

3. Proposed method

In the proposed method, each node selects a cluster head in a distributed manner. A node may choose itself as the cluster head and directly send data to the sink, or it may choose another node as its cluster head. After calculating the importance of its neighboring nodes in a distributed manner, each node selects its cluster head.

Assuming a wireless sensor network is defined as a graph $G = (V, E)$, where V is the set of nodes in the network (i.e., the sensor nodes) and E is the edges of the graph. An edge $e = (u, v) \in E$ if and only if

a) $u \in V$ and $v \in V$

b) v is within the transmission range of u.

It should be noted that G is an undirected graph, meaning if edge $e = (u, v) \in E$ then edge $e' = (v, u) \in E$ as well.

The proposed algorithm is distributed, and each node executes the method separately. The flowchart of the proposed method is shown in Figure 1. To select the cluster heads, the following steps must be performed for each node in a distributed manner.

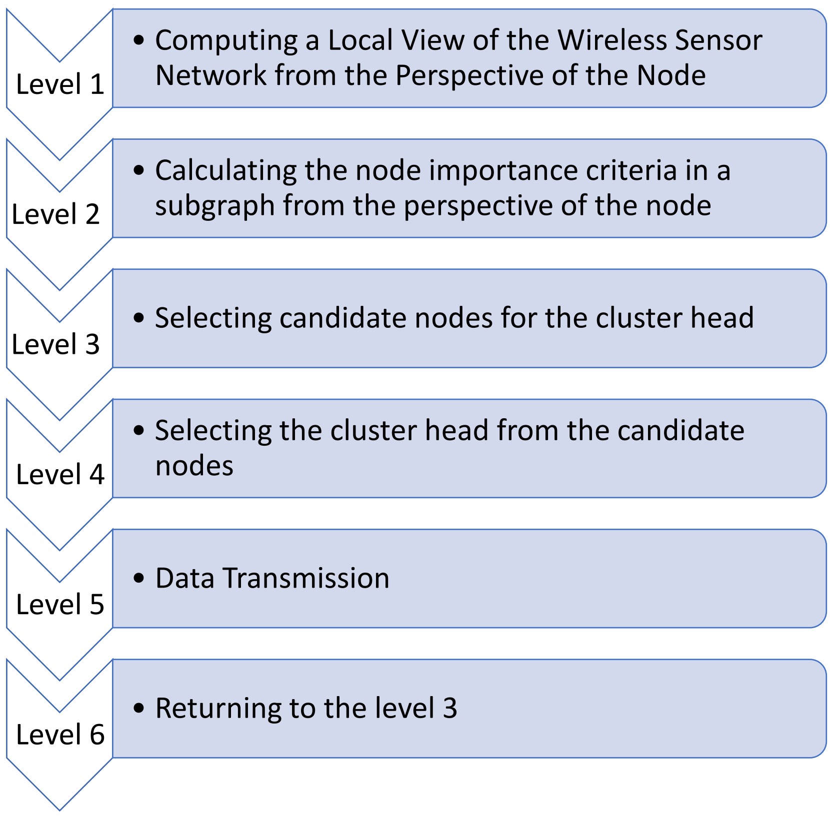

Figure 1 . The flowchart of the proposed method

3. 1. Computing a Local View of the Wireless Sensor Network from the Perspective of the Node

At this step, a local view of the wireless sensor network is created from the perspective of the node. The local view $\mathbf{G_1}\ (\mathbf{V_1}, \mathbf{E_1})$ of node $\mathbf{v_1}$ is a subgraph of the graph **G** as follows:

A) Node v_1 exists in the subgraph G_1; mathematically, $v_1 \in V_1$.

B) All nodes within the reach of v_1 in the original graph exist in the subgraph G_1; mathematically, for any v such that $(v_1, v) \in E$, then $v \in V_1$.

C) All nodes within the range of a such as v, where v itself is within the range of node v_1, are located in subgraph G_1. In other words, $u \in V_1$ if there exists at least one node v such that $(v_1, v) \in E$ and $(v, u) \in E$.

D) The set of edges in subgraph G_1 includes all possible edges using members of set V_1 provided that the edge is present in graph G. In mathematical terms, for edge $e = (u, v) \in E_1$ where $u, v \in V_1$ and $e \in E$.

3. 2. Calculating the node importance criteria in a subgraph from the perspective of the node

The measure of a node's importance indicates the extent to which a node can act as a transfer intermediary in terms of the shortest paths between any two nodes in a wireless sensor network. Therefore, the larger value of this criteria shows the more important the node. Additionally, considering the local view from the perspective of the node, the larger value of this criteria, shows that the node can be connected to other nodes in relatively short paths. The importance measure of node v_1 is calculated from the following equation:

$$NI(v_1) = \sum_{\substack{u,v \in V_1, \\ u \neq v \neq v_1}} \frac{\rho_{uv}(v_1)}{\rho_{uv}} \qquad (1)$$

where ρ_{uv} represents the number of shortest paths between two nodes u and v. Note that the size of the shortest path between nodes u and v may be equal to 3 and there may be 7 different paths of size 3 to get from node u to v. In this case, ρ_{uv} will be equal to 7. Also, $\rho_{uv}(v_1)$ indicates the number of shortest paths between two nodes u and v that pass-through node v_1.

An important point to note in the above equation is that ρ_{uv} cannot have a value of zero. The reason for this is that there is always at least one path between two nodes. In other words, two nodes are always connected. Node u is directly or at most one intermediary node away from node v_1. Similarly, node v is also directly or at most one intermediary node away from node v_1. In this case, there is a communication path between nodes u and v.

3. 3. Selecting candidate nodes for the cluster head

In this stage, candidate nodes for the cluster head are selected for each node v_1. Node v_1 receives the energy of all nodes in the subgraph G_1 through a message. Then, nodes that its energy is not less than that of node v_1 and who also have at least 40% of their initial energy remaining are considered as candidate nodes for the cluster head.

3. 4. Selecting the cluster head from the candidate nodes

In this stage, each node chooses a node from the candidate nodes as its own cluster head that has a higher importance level in the subgraph G_1. If there are multiple nodes with the same maximum importance criteria, the node that has already been chosen as a cluster head by another node in the same stage is selected as the cluster head. This process is also carried out in a distributed manner. For this purpose, each node that chooses another node as its cluster head sends a message to it, and the cluster head confirms the selection. This sending and receiving of cluster head selection confirmation messages has two main benefits: First, when a node has multiple candidate cluster heads with the same maximum importance criteria, sending a message can determine whether a node has already been chosen as a cluster head by other nodes or not. The second benefit is that the cluster head node becomes aware that it is responsible for collecting, processing, and compressing the data of other nodes and must send the information to the sink node after compression. If no candidate node exists in the previous stage, the node itself sends the information to the sink node as the cluster head in this stage.

3. 5. Data Transmission

All nodes are responsible for transferring their information to the cluster head or sink node. The energy required to transmit k bits of data to a node at distance d is calculated as follows:

$$E_{TX} = \begin{cases} k(E_{elec} + \varepsilon_{fs}.d^2) & d < d_0 \\ k\left(E_{elec} + \varepsilon_{mp}.d^4\right) & d > d_0 \end{cases} \quad (2)$$

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \quad (3)$$

where d_0 is the threshold distance for selecting the transmission model in meters. If the distance is less than the threshold, the free space model is used for transmission, otherwise the multi-path model is used. The coefficients in the above equations are defined as follows:

E_{elec}: The energy required to start the transmitter per bit in nano joules per bit (nJ/bit).

ε_{fs}: The energy consumed per bit for starting the transmission amplifier in the free space transmission model, in picojoules per bit multiplied by square meters ($pJ/(m^2. bit)$).

ε_{mp}: The energy consumed per bit for starting the transmission amplifier in the multi-path transmission model, in picojoules per bit multiplied by the fourth power of the distance ($pJ/(m^4. bit)$).

The energy required to receive k bits of data is calculated as follows:

$$E_{RX} = k. E_{elec} \quad (4)$$

Also, the energy consumed for aggregating m messages with length k bits is calculated as follows:

$$E_A = m. k. E_{DA} \quad (5)$$

where E_{DA} is the energy consumption for message aggregation in nanojoules per bit-signal, calculated by multiplying the length of the message by the number of messages(Devika and Saravanan 2022; AshimaVijan and Verma 2014).

3. 6. Returning to the selection of a cluster for the next time interval

After each time interval, each node proceeds to the third stage and continues the process.

4. Evaluations

In order to evaluate the proposed method, a wireless sensor network with the specifications listed in the Table 1 has been designed. Various experiments have been conducted with different numbers of sensors and message lengths. If a parameter of the network is not specified in each experiment, the values in the Table 1 have been used. In addition, the positions of the nodes have been randomly placed in the environment.

The experiments were done using $\text{Matlab } 2020$ on a computer with an $\text{Intel Core i7} - 6500\ 2.59\text{GHz}$ CPU, $8\ \text{GByte}$ RAM, and $\text{Microsoft Windows } 10$ operating system.

Table 1. The parameters of the wireless sensor network.

Parameters	Values
Size of the network environment	$100 \times 100\ \mathrm{m}^2$
Position of the sink node	$(\mathrm{x}, \mathrm{y}) = (50, 50)$
Number of nodes	50
Message size	$2000\ \mathrm{bit}$
Threshold limit	$\mathrm{d}_0 = 87.7058$
Initial energy of the nodes	$2\mathrm{J}$
$\mathrm{E}_{\mathrm{elec}}$	$50\ \mathrm{nJ/bit}$
$\varepsilon_{\mathrm{fs}}$	$10\ \mathrm{pJ/(m^2.bit)}$
$\varepsilon_{\mathrm{mp}}$	$0.0013\ \mathrm{pJ/(m^4.bit)}$
E_{DA}	$5\ \mathrm{nJ/(bit.signal)}$

4. 1. Evaluation Criteria

In this section, four evaluation criteria have been used to evaluate the proposed method. These criteria are listed below:

A) Time of death of the first node in the network.

B) Time of death of the last node in the network.

C) Remaining energy in the network over time.

D) Plot of the number of active (alive) nodes over time.

4. 2. Simulation Results

In this section, the proposed method is evaluated and discussed in various scenarios, including sparse, dense, and regular networks.

4. 2. 1. Evaluating the Proposed Method on a Network

In this subsection, the proposed method is implemented on the wireless sensor network mentioned in the above table for evaluation. Two criteria are used to evaluate the proposed method: the average network energy per moment and the number of live nodes per moment.

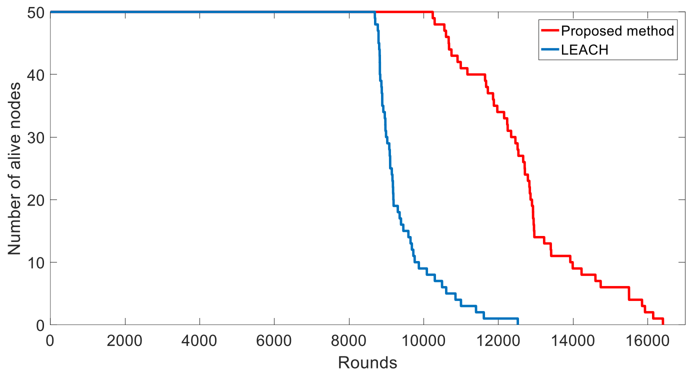

Figure 2. Number of alive nodes over time for a network with 50 initial nodes

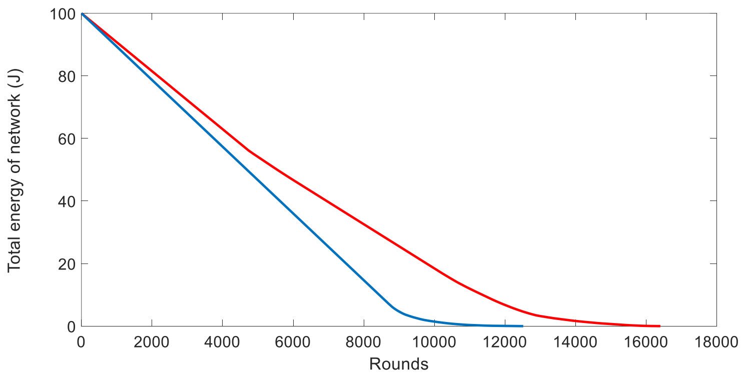

Figure 3. Total network energy over time for a network with 50 initial nodes

4. 2. 2. Evaluation of Proposed Method in a Sparse Network

In this section, the proposed method has been evaluated in a sparse network with 20 sensor nodes. As shown in the figures, the proposed method has effectively managed the network energy consumption.

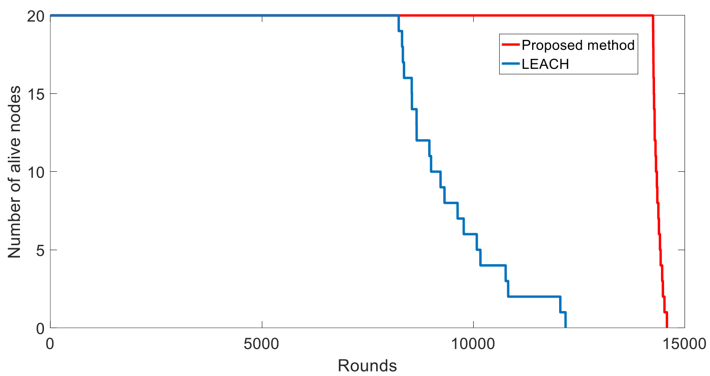

Figure 4. Number of alive nodes over time for a sparse network.

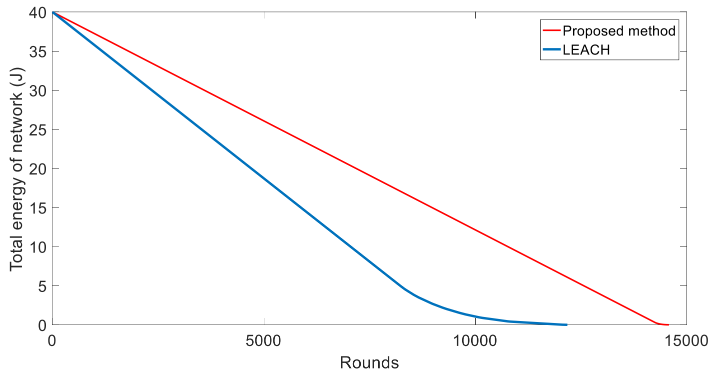

Figure 5. Total network energy over time for a sparse network.

4. 2. 3. Evaluation of Proposed Method in a Dense Network

In this section, the proposed method has been evaluated on a dense network with 100 nodes. The results show that the proposed method performs better than the LEACH method in terms of energy consumption.

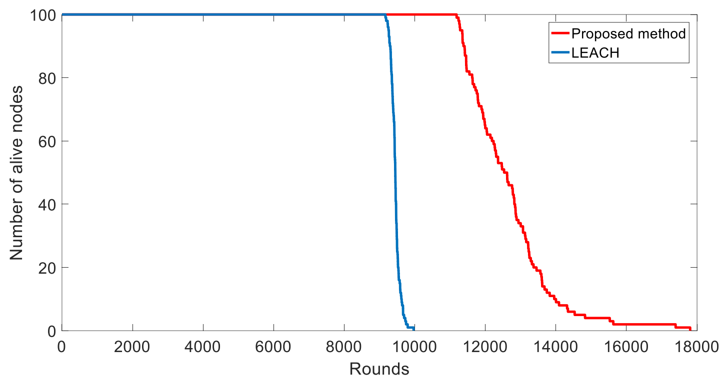

Figure 6. Number of alive nodes over time for a dense network.

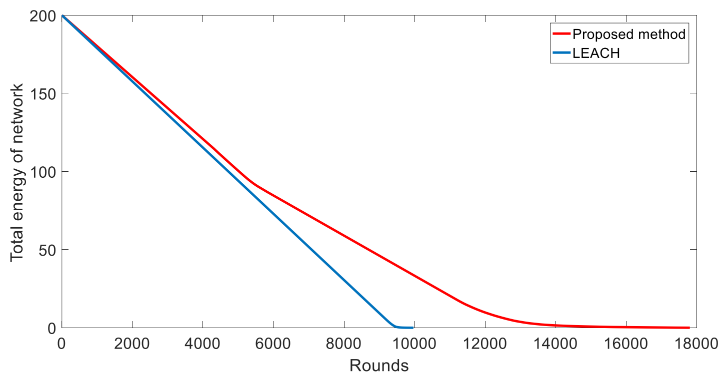

Figure 7. Total network energy over time for a dense network.

4. 2. 4. Evaluation of First Node Death Time in Network

In this section, the first node death time in the network has been evaluated. The evaluation has been done for different values of the initial number of nodes in the network. In all cases, the proposed method performs better than the LEACH method.

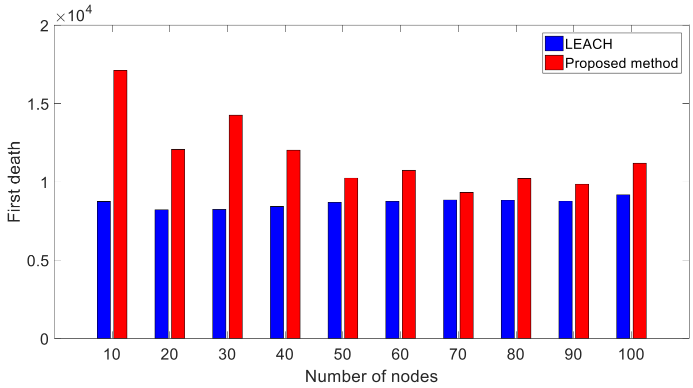

Figure 8. First node death time based on different initial node numbers.

4. 2. 5. Evaluation of Last Node Death Time in Network

In this section, the last node death time in the network has been evaluated. In other words, this is the time when the last node in the network also loses its energy and the entire network is destroyed. The evaluation has been done for different values of the initial number of nodes in the network. In all cases, the proposed method performs better than the LEACH method.

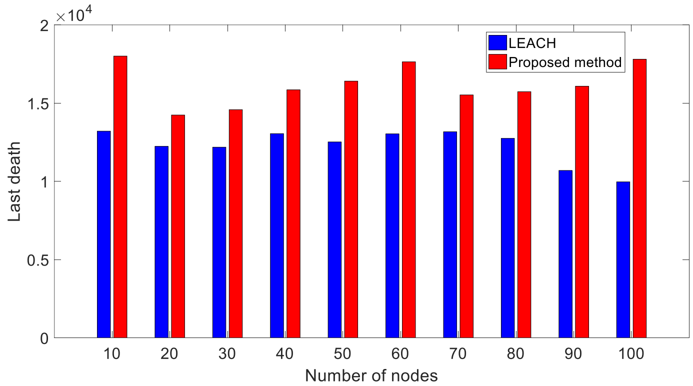

Figure 9. Last node death time based on different initial node numbers.

4. 2. 6. Evaluation of Proposed Method on a Regular Network

In this subsection, the proposed method was tested on a regular wireless sensor network. In this experiment, nodes are placed regularly in the environment. The arrangement of nodes is shown in Figure 10. Figure 11 shows the number of live nodes in the network over time for a regular network with 64 nodes. Figure 12 shows the total energy of the network over time for a regular network with 64 nodes.

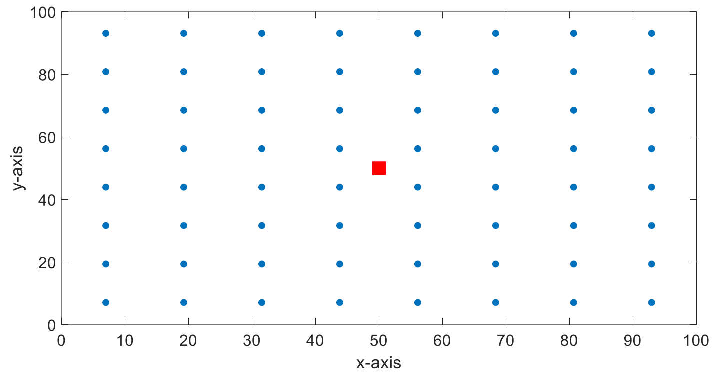

Figure 10. Regular arrangement of 64 nodes.

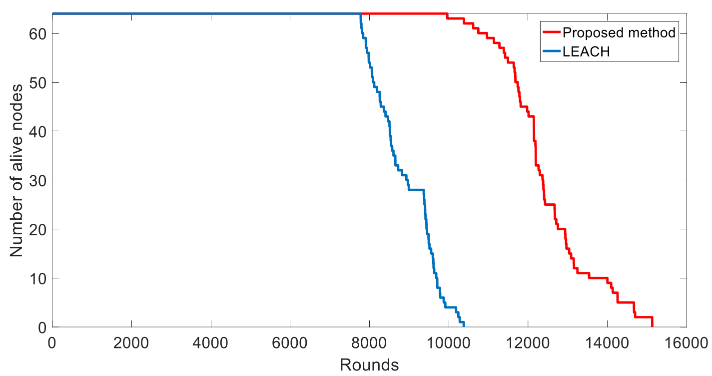

Figure 11. Number of alive nodes in a regular network with 64 nodes over time.

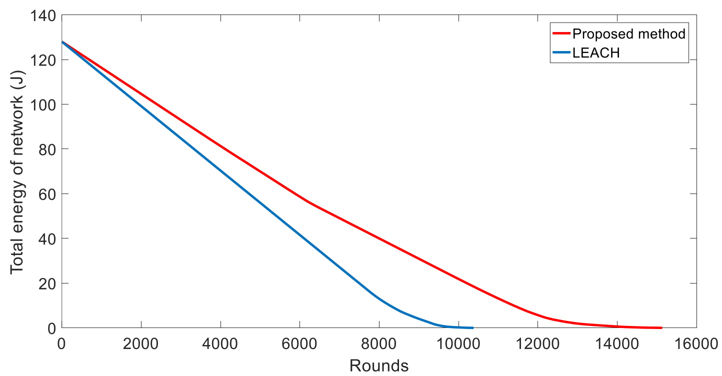

Figure 12. Total energy of a regular network with 64 nodes over time.

5. conclusion

In this paper, a novel method for energy management in wireless sensor networks is proposed. The proposed method is executed in a distributed manner by each node. The proposed algorithm was evaluated in various scenarios, and the results demonstrate its capability in energy management.

References

Adnan, Md Akhtaruzzaman, Mohammd Abdur Razzaque, Ishtiaque Ahmed, and Ismail Fauzi Isnin. 2013. 'Bio-mimic optimization strategies in wireless sensor networks: A survey', Sensors, 14: 299-345.

Alsharafat, W., A. Al-Shdaifat, K. Batiha, and A. AlSukker. 2022. 'A New Crossover Methods and Fitness Scaling for Reducing Energy Consumption of Wireless Sensor Networks', IEEE Access, 10: 93439-52.

Arora, Vishal Kumar, Vishal Sharma, and Monika Sachdeva. 2016. 'A survey on LEACH and other’s routing protocols in wireless sensor network', Optik, 127: 6590-600.

AshimaVijan, ShivenduDubey, and Ashok Verma. 2014. 'A Distributed Energy Efficient Cluster Based Routing Scheme for Wireless Sensor Network using Particle Swarm Optimization', International Journal of Communication and Networking System, 3: 291-304.

Chouikhi, Samira, Inès El Korbi, Yacine Ghamri-Doudane, and Leila Azouz Saidane. 2015. 'A survey on fault tolerance in small and large scale wireless sensor networks', Computer Communications, 69: 22-37.

Devika, E, and A Saravanan. 2022. 'AI-WSN: Direction of Arrival Estimation Based on Bee Swarm Optimization for Wireless Sensor Networks', Journal of Information Technology Management, 14: 69-86.

Eletreby, Rashad M, Hany M Elsayed, and Mohamed M Khairy. 2014. "CogLEACH: A spectrum aware clustering protocol for cognitive radio sensor networks." In 2014 9th international conference on cognitive radio oriented wireless networks and communications (CROWNCOM), 179-84. IEEE.

Ferreira, Adrian Carlos, Marcos Aurélio Vilaça, Leonardo B Oliveira, Eduardo Habib, Hao Chi Wong, and Antonio A Loureiro. 2005. "On the security of cluster-based communication protocols for wireless sensor networks." In Networking-ICN 2005: 4th International Conference on Networking, Reunion Island, France, April 17-21, 2005, Proceedings, Part I 4, 449-58. Springer.

Gandomi, Amir Hossein, Gun Jin Yun, Xin-She Yang, and Siamak Talatahari. 2013. 'Chaos-enhanced accelerated particle swarm optimization', Communications in Nonlinear Science and Numerical Simulation, 18: 327-40.

Handy, MJ, Marc Haase, and Dirk Timmermann. 2002. "Low energy adaptive clustering hierarchy with deterministic cluster-head selection." In 4th international workshop on mobile and wireless communications network, 368-72. IEEE.

Heinzelman, Wendi B, Anantha P Chandrakasan, and Hari Balakrishnan. 2002. 'An application-specific protocol architecture for wireless microsensor networks', IEEE Transactions on wireless communications, 1: 660-70.

Heinzelman, Wendi Rabiner, Anantha Chandrakasan, and Hari Balakrishnan. 2000. "Energy-efficient communication protocol for wireless microsensor networks." In Proceedings of the 33rd annual Hawaii international conference on system sciences, 10 pp. vol. 2. IEEE.

Mahapatra, Rajendra Prasad, and Rakesh Kumar Yadav. 2015. 'Descendant of LEACH based routing protocols in wireless sensor networks', Procedia Computer Science, 57: 1005-14.

Ordouei, Mohammad, and Touraj BaniRostam. 2018. 'Integrating Data Mining and Knowledge Management to Improve Customer Relationship Management in Banking Industry (Case Study of Caspian Credit', Int. J. Comput. Sci., 3: 208-14.

Ordouei, Mohammad, Ali Broumandnia, Touraj Banirostam, and Alireza Gilani. 2023. 'Optimization of energy consumption in smart city using reinforcement learning algorithm', International Journal of Nonlinear Analysis and Applications.

Ordouei, Mohammad, and Iman Namdar. 2018. 'Web Robot Detection Based On Fuzzy System and PSO Algorithm', Indian Journal of Computer Science, 7: 272-78.

Salim, Ahmed, Walid Osamy, and Ahmed M Khedr. 2014. 'IBLEACH: intra-balanced LEACH protocol for wireless sensor networks', Wireless networks, 20: 1515-25.

Sharma, N., and V. Gupta. 2020. "Meta-heuristic based optimization of WSNs energy and lifetime-A Survey." In 2020 10th International Conference on Cloud Computing, Data Science & Engineering (Confluence), 369-74.

Singh, S. K., P. Kumar, and J. P. Singh. 2017. 'A Survey on Successors of LEACH Protocol', IEEE Access, 5: 4298-328.

Singh, V Kumar, and Vidushi Sharma. 2014. 'Elitist genetic algorithm based energy balanced routing strategy to prolong lifetime of wireless sensor networks', Chin. J. Eng, 2014: 1-6.

Thiyagarajan, N., and N. Shanmugasundaram. 2022. "An Investigation on Energy Consumption in Wireless Sensor Network." In 2022 8th International Conference on Advanced Computing and Communication Systems (ICACCS), 1359-64.

Tyagi, Sudhanshu, and Neeraj Kumar. 2013. 'A systematic review on clustering and routing techniques based upon LEACH protocol for wireless sensor networks', Journal of Network and Computer Applications, 36: 623-45.

Voigt, Thiemo, Adam Dunkels, Juan Alonso, Hartmut Ritter, and Jochen Schiller. 2004. "Solar-aware clustering in wireless sensor networks." In Proceedings. ISCC 2004. Ninth International Symposium on Computers And Communications (IEEE Cat. No. 04TH8769), 238-43. IEEE.

Xu, DaWei, and Jing Gao. 2011. 'Comparison study to hierarchical routing protocols in wireless sensor networks', Procedia Environmental Sciences, 10: 595-600.