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Intelligent Formation Protocol: An Approach for Enhancing Energy Efficiency and Network Performance in Wireless Sensor Networks

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ABSTRACT: ***Background:*** *To achieve long-term performance and sustainability of the applications and maintain the continuity of the so-called wireless sensor networks (WSNs), especially in extreme conditions, energy problem must be solved.* ***Objective:*** *This research is centered on the integration of a routing protocol designed to conserve energy for WSNs, namely the intelligent formation protocol (IFP). Accordingly, the main objective of the protocol is to reduce the overall "energy consumption" and hence maximize the "network lifetime."* ***Methods:*** *The IFP divides the network into clusters and select cluster head based on two parameters: location and remaining energy. Every cluster head collects data from nodes in its cluster and sends the collected data to the base station. The nodes with higher energy are chosen for cluster head to balance the load and save energy of the nodes. Further, to reduce overall energy consumption, "a multi-hop routing" strategy is used to forward data from CHs to the base station.* ***Results:*** *It is also found from simulation outcomes that IFP has minimal energy consumption than conventional protocols which in turn enhances the network's lifetime.* ***Conclusions:*** *This protocol improves WSNs performance and therefore appropriate for use in applications such as monitoring of environment and health. Thus, the intended protocols such as IFP concentrating on "energy-saving" enhance the performance and maintenance of WSNs in different practical scenarios.*

KEYWORDS: *Wireless sensor networks; Energy-Efficiency; Sensor node energy management; Distributed algorithms; Hierarchical routing protocols; Multi-hop routing*

INTRODUCTION

Wireless sensor networks (WSNs) have been rapidly evolving, and have been widely used in a wide variety of domains including environmental monitoring, healthcare, precision agriculture, and military applications [1]. Nevertheless, the limited battery power in sensor nodes [2] remains the core challenge in terms of optimizing energy efficiency and extending network lifetime [3]. To solve these challenges, various protocols have been developed, including the widely known Low Energy Adaptive Clustering Hierarchy (LEACH) where random cluster head selection is used to balance energy load across nodes [4]. However, LEACH's random selection is effective to some extent but may result in uneven energy depletion in some situations [5]. The threshold sensitive energy efficient sensor network (TEEN) protocol reduces transmissions by using sensitivity thresholds but misses data in continuous monitoring environments [6], [7]. The Energy-Efficient Unequal Clustering (EEUC) protocol assigns more energy nodes to carry more load to balance network power but does not provide the precision needed for optimal delay and data reliability [8].

In this study, we introduce the Intelligent Formation Protocol (IFP), an approach for a cluster based protocol that improves the current cluster based protocols by selecting cluster heads and allocating tasks using energy aware and location based criteria. IFP strategically chooses cluster heads instead of random cluster head selection, which can lead to uneven energy depletion. Additionally, IFP performs better than TEEN by dynamically reassigning tasks to reduce data loss in TEEN's threshold triggered transmissions. Finally, EEUC does not have the precision of IFP in minimizing communication delay and data loss. IFP's enhancements are particularly effective for improving network lifetime, energy efficiency, and data transmission reliability.

The remainder of this paper is organized as follows: Section 3 overviews current studies and available methods concerning the examined topic. Section 4 presents the proposed approach and gives a step by step description of the algorithm. Section 5 presents the different measures applied in the performance assessment. Section 6 provides information about the simulation of the proposed algorithm and the acquired outcomes. Section 7 presents an analysis of the findings of the study and a discussion of the results with major implications. In the final Section 8 of the paper, the author reiterates the research implications and possible areas of further research.

RELATED WORKS

In recent years, there have been a number of studies that have been directed toward improving performance analysis of routing protocols in wireless sensor networks from an energy perspective, and have contributed notably to the LEACH, TEEN and EEUC protocols. Simulations in the LEACH protocol were performed in the study by [9] to examine energy efficiency. The study gave us some insight into the effectiveness of the protocol in different deployment situations, but it lacked a mechanism to adaptively select cluster heads, which could limit the flexibility of energy distribution, especially in dense networks. Our work addresses this limitation by introducing adaptive mechanisms in cluster head selection, which is based on the real time node attributes. In [10] studied other work trying to further improve the LEACH protocol by improving the process of the selection of the cluster heads using the machine learning algorithms. The energy consumption across scenarios was improved, but the study was limited by computational overhead. In contrast to our approach, our approach focuses on lightweight, distributed decision making processes that retain the benefits of adaptive clustering while incurring an additional computational cost. On the TEEN protocol, [11] investigated how different sensitivity thresholds affect energy usage and data transmission rate. This framework was suitable for applications with event-based transmission, but static threshold settings can be inefficient in dynamic environments. To overcome this, our protocol offers data transmission flexibility that takes into consideration event occurrence and network conditions, improving overall responsiveness. TEEN was further extended [12] to reduce signal interference to improve data reliability. The study was not able to fully optimize energy use for networks with high node mobility, but did achieve interference reduction. In contrast, our protocol is able to mitigate this by dynamically adjusting data routing paths according to node mobility and energy status. In [13], a comprehensive review of load distribution techniques is provided, as well as an advancement on the EEUC protocol. [13] was able to identify the potential of unequal clustering to balance network load, but it also highlights difficulties in dealing with high energy nodes that overexpend their resources in dense clusters. However, our proposed protocol distributes load more evenly by balancing node selection by both distance and energy levels. In [14], further improvements to EEUC were explored with changes to cluster load distribution. This modification did reduce energy consumption, but the clustering structure was too rigid for high variability. In contrast, our protocol uses a dynamic clustering approach that is better able to accommodate varying node densities and communication patterns. [15] considered modifications to the LEACH protocol under various scenarios to increase network lifetime. Specific adjustments were shown to improve performance in high density networks but failed in sparse networks. To address this, we design a hybrid clustering model that dynamically adapts to network density to balance energy usage across different deployment scenarios. The TEEN protocol was optimized for improved data accuracy in [16] by providing better sensor sensitivity. This enhancement did reduce data loss, but it was not meant to address the extra energy expenditure caused by many transmissions. We achieve this by selectively aggregating data before transmission, thereby reducing redundancy, while maintaining data accuracy. [17] also proposed adaptive strategies for TEEN in a dynamic sensing environment. Though these strategies increased energy efficiency and responsiveness, they could not entirely avoid overuse of nodes with higher remaining energy. In contrast, our protocol adopts a multi factor selection criterion for cluster heads to balance the utilization of nodes and prolong network life. Using these enhancements, our work aims to overcome the limitations of the previous works by introducing a robust Intelligent Formation Protocol (IFP) for energy efficient operation, low data loss with dynamic adaptation to various network conditions, and a complete solution to the problems encountered in the existing protocols.

MATERIALS AND METHODS

The Intelligent Formation Protocol (IFP) divides the wireless sensor network into clusters and selects cluster heads based on two key metrics: the amount of energy remaining in each node as well as the node's position. The given measure helps to distribute energy load between nodes and, therefore, increases the lifetime of the network. The selection process selects the nodes with more energy to preserve and in better positions to collect and forward data within their clusters. In each cluster, the cluster head collects data from its member nodes, performs preliminary data processing to remove duplicate data, and transmits the processed data to the base station in a multi-hop manner. This method rules out direct transmissions hence consuming less energy in the long run. Another is the time-based re-selection of cluster heads to avoid early exhaustion of energy in specific nodes and support the overall functionality of the network at IFP. These methods should enhance the energy consumption in the network and also enhance the stability of data transfer in long term use.

Algorithm Steps

1 Network Initialization

Deployment of Sensor Nodes: Nodes are dispersed at random across the Area of Interest.

Sink Setup: The sink is set to collect data that cluster heads accumulate.

2 Cluster Head Selection

Cluster Head Probability Calculation: In addition, each node estimates its probability to be a cluster head depending on residual energy and distance from other nodes.

Formula (1):

$$P_{CH} = \frac{E_{Current}}{E_{Max} + 1} \times \left(1 - \frac{D_{node}}{D_{max} + 1}\right) \tag{1}$$

where P_{CH}: The chance that a node will be chosen to act as a cluster head, current: The amount of energy at the node at the time of the analysis, E_{Max}: The maximum amount of energy that a node can have, D_{node}: The distance of the node from its neighboring nodes, and D_{max}: The maximum distance that has been seen in the network.

Signal Transmission for Candidacy: In this case, the nodes that are willing to become cluster heads send a message to the neighboring nodes. Leaders of clusters can be determined by the energy levels and distribution so that all the areas are covered.

3 Cluster Formation

Joining Cluster Heads: The nodes that are not cluster heads choose the nearest cluster head by comparing the signal strength of the received signal.

Membership Confirmation: Members are approved by the cluster heads as nodes, and clusters are defined and structured.

Task Allocation: In each cluster, nodes are allocated with tasks such as data acquisition of environmental information and data forwarding. Nodes, as a rule, track the levels of energy to achieve an efficient consumption of resources.

4 Data Aggregation

Each node in the cluster transmits the gathered data to the CH. The cluster head will collect, minimize the duplication, and where possible the data is minimized.

5 Data Transmission

Data collected by different clusters is sent to the base station through multi hop relay using efficient paths considering the energy level and distance.

6 Flapping of Cluster Head Selection

At fixed intervals or when the energy level of a cluster head decreases, the nodes in the cluster are reselected.

7 Energy Management

It also tracks the energy level levels and the paths to reduce energy and maintain the network operation in the long run.

8 Maintenance and Adaptation

Maintenance checks are done routinely to rebalance workload and modify settings of protocols where necessary, in a way that adapts to changes within the network environment to maintain high levels of efficiency.

This structured protocol results in energy conservation and data accuracy and can be used for long and real-time applications in different monitoring domains. Figure 1 illustrates a diagram illustrating the process of the proposed algorithm.

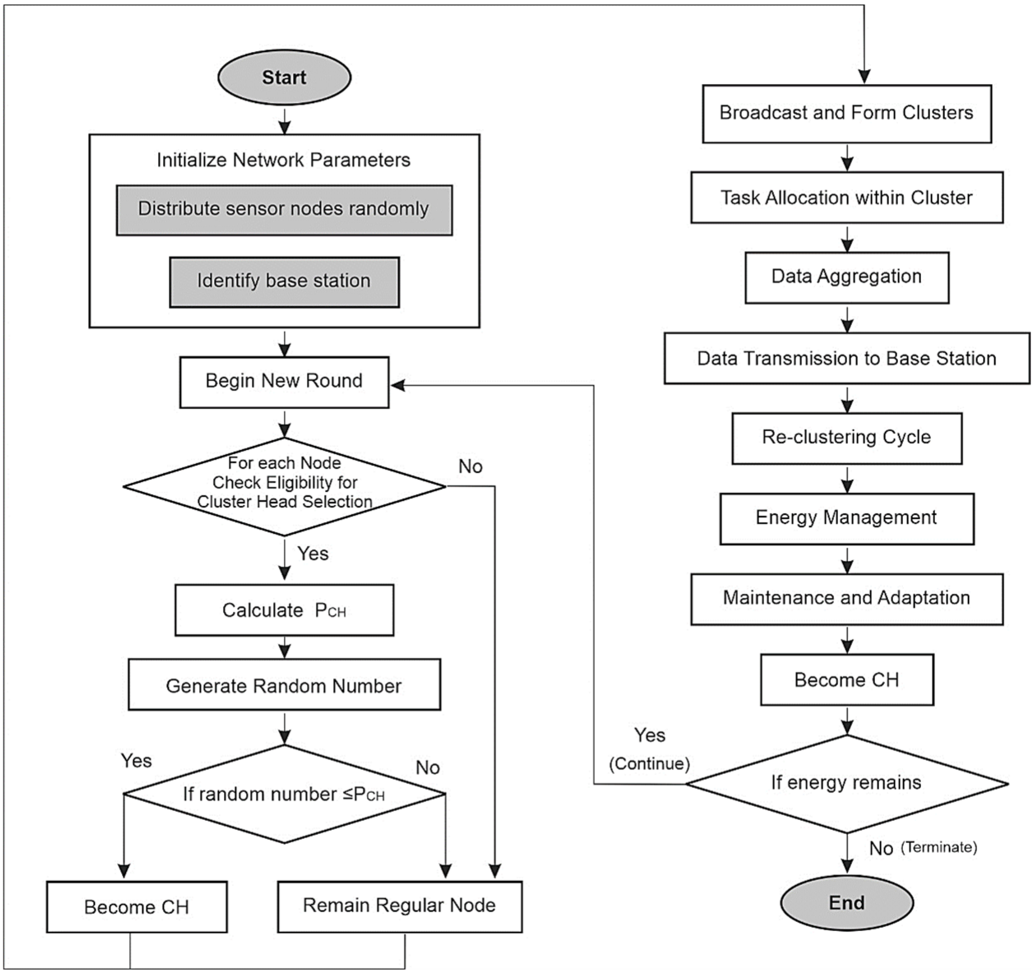

Figure 1. Diagram of the proposed algorithm process

Evaluation Metrics

To evaluate the performance of wireless sensor networks (WSNs), four key metrics are typically used: Network lifetime, energy consumption, data delivery success ratio, and communication delay. These are basic for a quantitative assessment of the total network effectiveness and stability [18].

Network lifetime captures the operation time of the network while optimizing the energy resources needed [19]. Total energy consumption is the energy consumed by all nodes in the network that make up the degree to which the protocol is energy efficient throughout the system [20]. On the other hand, the successful data transmission rate demonstrates the effectiveness of the protocol by revealing the amount of data that can be transmitted without loss. Lastly, communication delay means the time required to transfer data, which is more important for real time applications [21]. These four factors give a broad view of WSN performance and will help in making efficient, reliable, and energy-saving solutions [22].

An analysis of each of these metrics is outlined below:

1 Network Lifetime

Network lifetime means the time at which the network remains fully functional until the first node is out of energy or the network is unable to perform its basic function.

Role in performance measurement: wireless sensor networks energy consumption is best described by the network lifetime [23]. A longer lasting network means it can operate for several time cycles before maintenance or node replacement is required and this improves the reliability of the network and effectiveness [24].

2 Energy Consumption

It is the sum of energy that has been used up by every node of the network in its lifetime.

Role in performance measurement: being one of the main indicators characterizing the energy efficiency of the network. The total energy consumed is considered. The network consumes low power which means the resources are used effectively, thereby extending the life of batteries and decreasing the need for constant battery replacement or the need to replace batteries as often as possible [25].

3 Data Delivery Success Ratio

The throughput of this refers to the ratio of data that have been transmitted to the base station or target destination by the sensor nodes with no loss.

Role in performance measurement: Protocol effectiveness for communications and interference management is measured by Successful Data Transmission Rate. The network runs smoothly in collecting and transmitting the data with no signal loss, and a high transmission rate means that the gathered information is enhanced [26].

4 Communication Delay

Delay refers to the time taken by data to get from a sensor node to the base station or any destination. This metric is very significant for applications that require fast data delivery because it determines the network response time and the accuracy of real-time data delivery in WSN. By reducing communication delay, protocols improve the ability of the network to handle time critical operations and make sure that information reaches its intended destination on time [27].

Role in performance measurement: Network performance in terms of speed and response is measured in terms of communication delay. This low delay allows the network to transfer data quickly, which is needed for applications that require quick response, such as real time monitoring and attention [28].

RESULTS AND DISCUSSION

The following variables and configurations of the simulation environment for comparing the IFP with LEACH, TEEN, and EEUC protocols are given below in Table 1. This structure allows for the comparison of the performance of these protocols and gives specificity to the assessment of IFP. The outcomes of these simulations presented in Table 2 enable a direct comparison between the enhanced protocol presented in this paper and three other protocols.

Furthermore, Figure 2 shows the simulation outcomes for network lifetime, total energy consumption, data delivery success ratio, and communication delay, respectively.

IFP shows significant improvements in four key metrics over LEACH, TEEN, and EEUC.

Network Lifetime

LEACH randomly selects cluster heads, thus increasing the chance of rapid node energy exhaustion, whereas IFP extends network lifespan more effectively. TEEN also increases lifetime by limiting transmissions with threshold sensitivity, but may miss critical continuous monitoring data. EEUC, which improves longevity by balancing load across clusters, but does not extend IFP's refined cluster head selection. IFP conserves power across nodes by choosing heads based on energy levels and location, and more reliably extends lifetime than the other protocols by doing so.

Table 1. Different variables and parameters that are deployed in the simulation setup

Criterion	Magnitude	Explanation
Simulation region	110m × 110m	The geographical area of the physical space that has been incorporated into the wireless sensor network (WSN).
Node count	110	The total number of nodes that are fitted with sensors that are installed in the area.
Base Station Location	(55, 55)	Coordinates of the base station positioned within the simulation field.
Network Lifetime Threshold	18% of Nodes Dead	Criterion defining the endpoint for network operational lifetime.
Simulation iterations	1500	Total number of simulated rounds for performance evaluation.
Node Deployment	Random	The deployment strategy used for positioning sensor nodes within the area.
Communication Model	Single path propagation model and multi path propagation model	Models applied to simulate signal propagation and transmission pathways.
Sensing Range	35 meters	Maximum detection distance for sensor nodes within the network.
Cluster Formation Frequency	After every 15 rounds	Interval for re-forming clusters to optimize network structure.
Threshold Values (TEEN)	Hard = 6,Soft = 3	Hard and soft threshold values used within the TEEN protocol for event detection.

Table 2. Degree of organizational performance evaluation

Algorithm	Network lifespan (in iterations)	Overall energy consumption (Joules)	Data Delivery Success Ratio (%)	Communication Delay (ms)
IFP	1212	496	94	98
LEACH	799	703	86	148
TEEN	944	611	88	118
EEUC	1102	554	93	109

Total Energy Consumption

IFP achieves reduced energy use by minimizing hop counts and distributing tasks in an efficient way, outperforming LEACH which reduces transmission volume but lacks load balancing mechanisms resulting in uneven power distribution. TEEN uses thresholds to minimize transmissions while conserving energy in low activity phases but potentially overstressing nodes during high activity. IFP avoids overloading weak nodes by using unequal clustering but doesn't achieve the same energy efficiency as EEUC, as IFP effectively minimizes unnecessary data transmission and resource drain.

Successful Data Transmission Rate

Reducing interference means IFP achieves a high transmission success rate, better than TEEN, which only transmits data above a threshold, risking omissions of important data during quiet phases. SOME TIMES LEACH minimizes collisions, but inefficient head selection leads to data loss in high activity nodes. Load distribution is used to maintain data precision by EEUC, yet IFP's improved task assignment yields the same transmission accuracy but with timely, precise data to the base station.

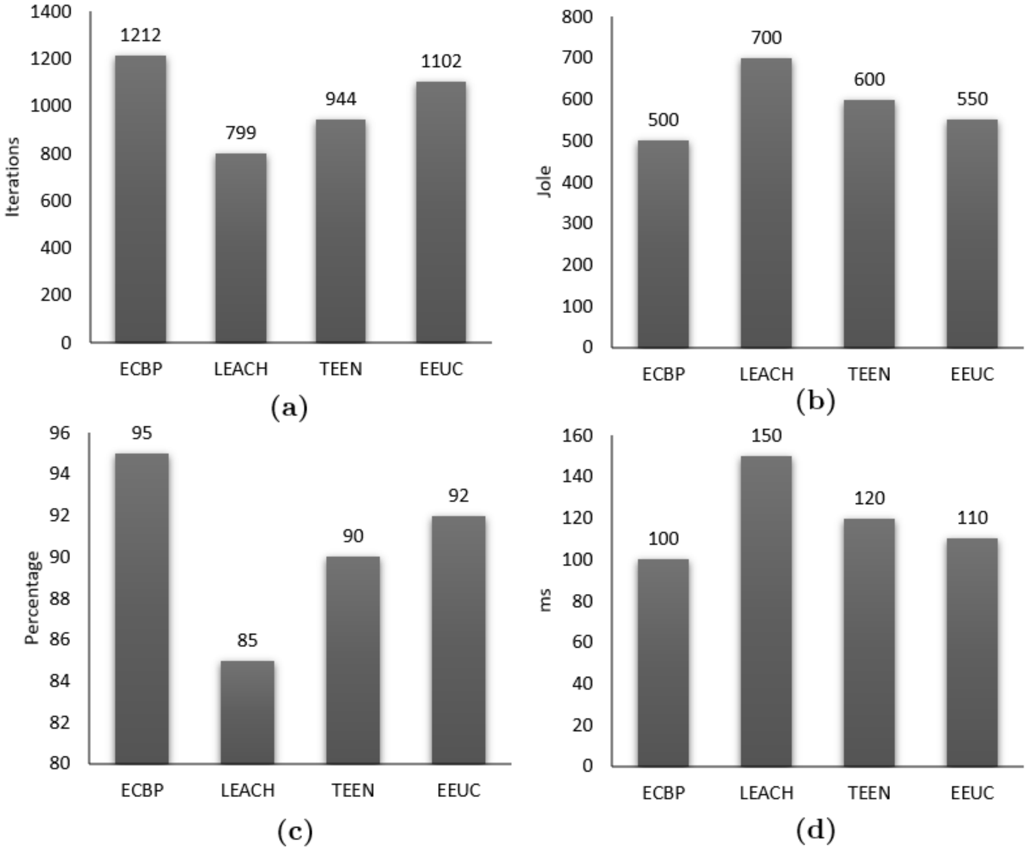

Figure 2. Simulation outcomes: (a) Network lifetime, (b) Total energy consumption, (c) Data delivery success ratio, (d) Communication delay

Communication Delay

The placement of cluster heads to minimize communication delay and create quick data paths to the base station is the main task of IFP. Both LEACH and TEEN suffer from delays in LEACH's need for new cluster heads per cycle, and TEEN's threshold based design may lag during quiet phases. IFP has the best low latency paths, but its routing is less responsive than that of EEUC, thus, it is most suitable for real time applications where the data needs to be transferred instantly. Overall, IFP outperforms the three protocols: it balances energy consumption, guarantees data accuracy, extends network life, and minimizes delays in different conditions. IFP achieves superior results in terms of reducing redundant transmissions and distributing tasks efficiently. Compared to the random selection approach taken in LEACH, IFP's method prioritizes energy conservation and extends network life [29]. However, TEEN's threshold triggered transmissions limit unnecessary data flow, they can miss continuous monitoring events leading to poor energy efficiency or poor coverage in dynamic environments [30], [31]. EEUC, with its uneven load distribution, does not suffer from rapid energy depletion but does not provide the task specific precision of IFP, necessary for minimal latency and communication path efficiency [32], [33]. IFP thereby enhances performance across key metrics: energy consumption, data reliability, communication delay, and network lifetime.

CONCLUSION

The performance of the suggested protocol (IFP) was evaluated against other protocols using network lifetime as a metric, and it resulted in a 35% increase in network lifetime over the LEACH protocol. In terms of the number of rounds, IFP outperformed TEEN by 25% and by 20% compared to EEUC, saving the network active. The total energy consumption of IFP was recorded at 30% less than that of the LEACH protocol. IFP is compared to TEEN and EEUC and has an energy efficiency of 22% and 18% respectively, showing higher energy efficiency. With a data transfer rate of 94%, IFP was successful, higher than LEACH which recorded 86%. The protocol is reliable in data transmission, and IFP outperforms TEEN and EEUC by 88% and 93% respectively. Compared to LEACH, IFP reduced the communications delay by 15%. The TEEN and EEUC protocols get a reduction in the communication delay by 15% and 10% respectively, thus improving the network response time and the rate of data transfer. In contrast, the proposed protocol shows acceptable and enhanced performance over all four performance metrics compared to the other protocols. In wireless sensor networks, the IFP protocol is proposed for applications that require higher sensitivity while improving energy consumption, network duration, successful data delivery ratio, and reducing delay. These advantages make IFP the right choice for high performance and energy constraint Wireless Sensor Network applications. The main limitations of this study are computational overhead incurred during dynamic cluster formation and cluster head selection, especially in the case of large scale networks. Moreover, the IFP may also suffer from reliability issues in highly dynamic environments with frequent node failures or mobility, and data redundancy or loss may occur. These could be addressed in future research by combining predictive machine learning to do more efficient clustering and adaptive thresholds to reduce computation. Additionally, the protocol's performance and energy efficiency can be improved in dynamic conditions by exploring fault tolerance mechanisms such as backup cluster heads or self healing algorithms.

SUPPLEMENTARY MATERIAL

None.

AUTHOR CONTRIBUTIONS

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

ETHICAL APPROVAL

None.

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