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Original Article

Energy-Efficient Routing Algorithms for Wireless Sensor Networks Using Swarm Intelligence

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Abstract - *WSNs have become significant in contemporary applications in the field of environmental monitoring, health care, and industrial automation. But these are limited by the fact that they are not powerful enough. In order to achieve a longer life span of networks and to ensure that data is delivered with greater reliability, there is a need to design routing protocols that are less energy-consuming. The paper suggests a new swarm intelligence routing algorithm, which combines both adaptive clustering and energy-efficient route optimization to optimize intra- and inter-cluster communication. The proposed approach is founded on the way swarm agents work in concert and modify routing decisions by residual energy, communication cost, and node density to maintain the energy consumption of the network within reasonable bounds. The simulation findings prove that our method enhances both the network lifetime and the ratio of packet delivery, achieves a throughput better than the traditional protocols, and minimizes the quantity of control overhead. This single-method design offers a resource-limited and rigorous scheme of resource-limited WSNs, which makes it especially suitable for realistic applications in energy-sensitive scenarios.*

Keywords - *Routing That Uses Less Energy, Swarm Intelligence, Clustering, Routing That Takes Energy into Account, The Lifespan of a Network.*

1. Introduction

WSNs consist of autonomous sensor nodes that are spatially distributed and used to measure physical or environmental parameters such as temperature, humidity, and pressure, and transmit the measured data to a central base station to be analyzed [1]. They find wide application in environmental monitoring and industrial automation systems and in health care and military surveillance due to their capability to provide real-time data from distances and inaccessible locations [2]. Among the challenges is the limited power capacity of sensor nodes, which primarily affects the network lifetime and performance [3]. The routing protocols could significantly contribute to energy management by setting the best paths to transfer data, less usage of energy, and the occurrence of failure of nodes is minimized [4]. The typical routing schemes, such as flat, hierarchical, and location, are primarily limited in terms of scaling, energy equilibrium, and responsiveness to dynamic network environments [5]. Swarm intelligence is a concept that is applied in the optimization of network challenges that are inspired by the collective behaviour of social organisms like ants, bees, and birds (Swarm intelligence, 2002). The Swarm Intelligence algorithm is decentralized, self-organizing, and adaptive, and hence can be used in efficient routing of energy in WSNs [7]. Through those algorithms, the sensor nodes can make decentralized decisions regarding the data forwarding and the cluster formation in accordance with (among other factors) residual energy, communication cost, and node density. Clustering techniques, together with swarm Intelligence, are used to reduce redundancy of messages and to distribute energy dissipation uniformly among the nodes to enhance network lifetime. Using energy-aware routing and adaptive clustering makes sure that high-energy nodes are utilized well and low-energy nodes are discarded over time. This is crucial for maintaining a network's operation [8]. Swarm Intelligence routing algorithms have been identified to be more efficient than conventional routing algorithms in terms of map delivery ratio, throughput, and control overheads. Moreover, the algorithms can be expanded for large-scale deployment of the WSN, as the decision-making process is localized to assist in reducing the need to know the network on a global scale. Despite these advantages, issues such as optimizing swarm parameters, the interaction between exploration and exploitation, and the latency of dynamically computed abodes continue to exist. The ongoing research is focused on developing hybrid methods that integrate swarm intelligence and energy-aware heuristics to enable effective, efficient, and reliable communication in sensor networks with resource constraints [9]. Lastly, swarm intelligence and energy-efficient routing are solutions to the energy consumption constraints of WSNs. These mechanisms can significantly enhance the network throughout the lifetime and the overall network operations through the mechanisms, which are decentralized decision-making, adaptive clustering, and energy-conscious path selection [10]. These methods should be invented to enable the construction of sustainable and scalable WSN applications in practice. The trend in the future is projected to be adaptive hybrid designs that further enhance the energy consumption, reliability, and durability in more complex sensor network environments [11].

2. Literature Review

Zeng et al. [12] provide the WSA-ICR approach, an energy-efficient routing strategy for Wireless Sensor Networks (WSNs) based on a whale swarm optimization framework. The algorithm provides a new energy efficiency goal function that takes into consideration both node energy and path length. Five aspects of the whale swarm algorithm are enhanced: individual coding, initialization, distance calculation, movement rules, and local search. The algorithm balances network energy and extends network lifetime by means of iterative counter-based routing. It has been demonstrated by simulation that WSA-ICR converges faster than current energy-sensitive routing algorithms, achieving better energy distribution among nodes and more robust network behavior; thus, it is very well adapted to WSNs with limited energy resources. Rose et al [13] present a hybrid algorithmic framework based on AGSO and Reinforcement Learning (RL), and ACO when WSNs are getting routed. The strategy is based on adaptive clustering, with cluster heads being chosen using AGSO, and only selected CHs are used to a base station to save on energy. RS finds the optimal routing options under network conditions, whereas ACO finds the optimal multi-path routing option under network conditions to maximize reliability and energy consumption. The strategy minimizes overheads in communications, harmonizes the energy usage, and extends the network lifespan. The results from the simulation show that the packet delivery ratio, throughput, power consumption, and end-to-end delay are all much better than the standard protocols like LEACH, HEED, and PSO. The protocols are also very reliable and flexible for how a WSN works. Priyadarshi et al [14] discuss the applications of Artificial Intelligence (AI) within WSNs to promote energy efficiency, reliability, and network performance. The application of AI algorithms enables dynamic monitoring of the battery-driven sensor nodes in different environments and locations, such as on land, underwater, and in industry. Another topic of the article is also concerned with bio-inspired algorithms that can assist in the optimal routing and clustering of the network to conserve energy and prolong network life. The article is able to address the most significant issues involving WSNs, including limited energy, restricted computation and storage, scalability, and fault tolerance, through clever approaches. The proposed solution is to apply AI to ensure that the WSNs become more sustainable and efficient in a broad spectrum of real-world conditions of deployment. Arun et al. [15] maintain that the study presents a routing algorithm of WSNs that operates without energy consumption and therefore uses Adaptive Sailfish Optimization (ASFO) and K-medoids clustering. The primary objective is to enhance the choice of cluster heads, thereby maintaining unchanged energy utilization, reducing node distance, and minimizing latency. The system uses a Cross-Layer Expedient Routing Protocol (E-CERP) to offer the shortest paths and dynamically calculate the network overhead. The performance metrics that we considered included a packet delivery ratio, a packet delay, throughput, power consumption, the lifespan of the network, and a packet loss rate. Findings reveal high performance, e.g., 100% PDR, low delay, and extended network lifetime relative to current protocols and justify the framework as a strong solution to energy-limited WSN deployments with a high QoS need.

3. Proposed Work

3.1. System Model and Network Assumptions

The suggested energy-efficient routing technique is based on a Wireless Sensor Network (WSN) that is made up of sensor nodes that are spread out randomly across a certain region. Additionally, each sensor node has limited battery capacity, as well as sensing, processing, and communication capabilities. When nodes are deployed, they are assumed to be stationary and can communicate wirelessly with neighboring nodes and a fixed base station located at a fixed position. The network is time-slotted, which means that each node periodically detects information about the environment and sends it to the base station via multihop communication. Localized decision-making presumes that nodes possess knowledge about their residual energy and the approximate positions of neighboring nodes. The communication model employs a first-order radio energy dissipation model to determine the amount of energy required, taking into account the distance of transmission and the message size. There are no assumed malicious attacks on the network, and the channel conditions are perfect, with very low packet loss and minimal interference. The cluster head data aggregation is seen to minimize unnecessary transfers, resulting in a decrease in the aggregate power consumption. The network architecture enables nodes to dynamically cluster together, allowing those with more remaining energy to serve as cluster leaders, while other nodes become member nodes. The principles of swarm intelligence help create clusters and routes, utilizing decentralized decision-making to optimize energy needs. The nodes communicate with their neighbors to share energy and location data and can form energy-efficient clusters themselves. This model enables the network to achieve long operational lifetimes, high data delivery ratios, and can respond to changes in the amount of energy a node has, without requiring global network information, making it scalable to large-scale sensor systems. Figure 1 depicts the system architecture.

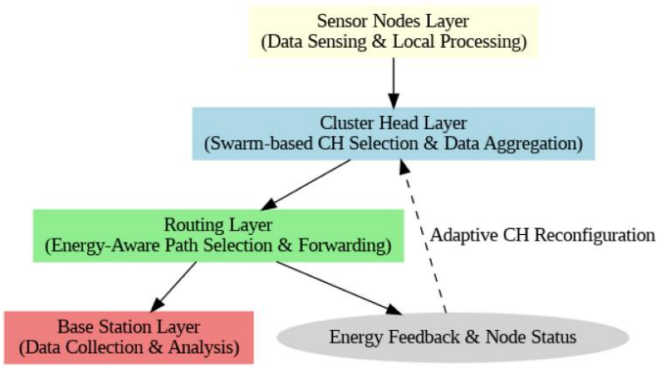

Fig. 1 System Architecture

3.2. Node Energy Model

The node energy model illustrates how energy is utilized and how the network is managed to operate in an environmentally friendly manner. A sensor node has a battery that only lasts for a short time, and it uses most of its energy for detecting data, processing it, and sending it wirelessly. A first-order radio model is used to determine the amount of energy consumed to send a k-bit message over a distance of d. This model takes into account the energy used by the transmitter electronics and the fact that an amplifier is needed for longer-range transmission. Likewise, the energy expended in receiving messages is proportional to the receiving bits. Nodes occasionally assess their remaining energy in order to engage in decision-making activities such as cluster formation and route choice. Figure 2 depicts the Network Topology with clusters for WSN. Energy-conscious measures are incorporated into the swarm intelligence algorithm to ensure that the swarm avoids overloading low-energy nodes and prefers high-energy nodes to carry out energy-demanding activities, such as serving as a cluster head or relaying packets to a destination through multiple hops.

The grouping of data at cluster heads is also part of the energy model, and it minimizes the number of sent messages by assembling many incoming messages into one smaller message. This algorithm can significantly reduce network energy usage and prevent the premature failure of nodes. Nodes are actively updating their energy status, thereby adapting to changing network conditions.

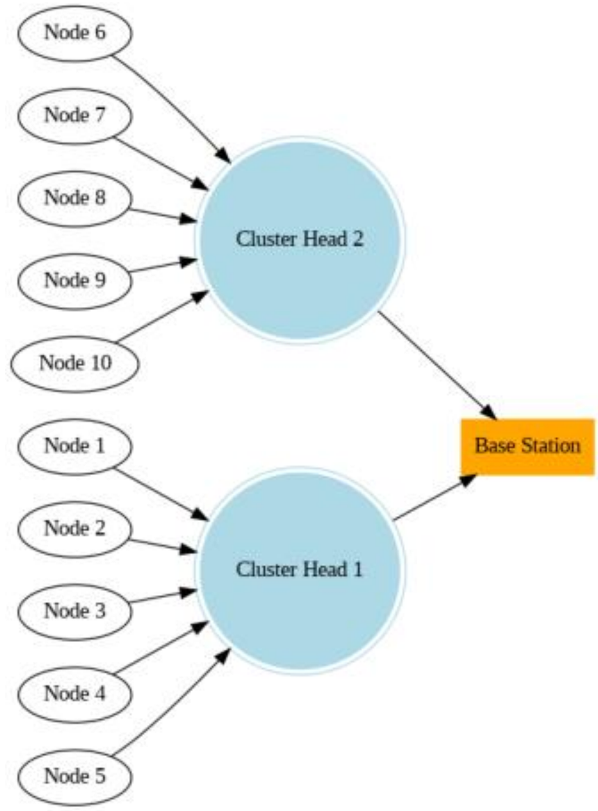

Fig. 2 WSN Network topology with clusters

With the integration of energy-aware routing and swarm intelligence, the energy model ensures balanced energy usage across nodes, thereby increasing network lifetime and enhancing reliability in a self-organizing and decentralized manner. The method presents a feasible system of applying energy-efficient communication to WSNs under resource-bound conditions.

3.3. Swarm Intelligence-Based Clustering Approach

The clustering system is based on swarm intelligence, which means that it utilizes the behavior of basic agents to create clusters that can grow and evolve independently. Figure 3 depicts the swarm intelligence-based clustering diagram. Residual energy, node density, and the proximity of a node to other nodes all affect whether a single sensor node can be employed as a cluster head. The concept of swarm intelligence is used to enable the group to work together to identify the best cluster heads. The nodes of larger energy and strategic location in the network are selected probabilistically, with the intention to act as cluster heads that ensure even distribution of energy and decrease the chance of early node drainage. After the cluster heads are selected, the member nodes connect to the nearest cluster head based on their distance and the cluster head's remaining energy. This decentralized clustering strategy enables nodes to communicate with each other locally without requiring knowledge of the global network. This makes it easy to scale up to big WSN installations.

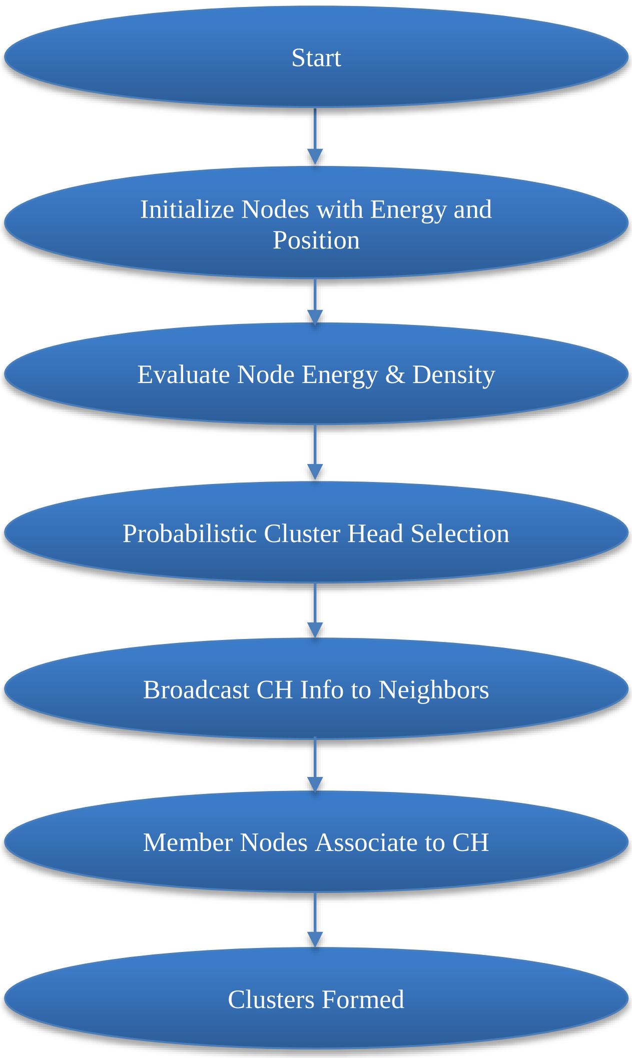

Fig. 3 Swarm intelligence-based cluster head

The approach uses swarm behavior to do iterative optimization. This implies that nodes share information with their neighbors to help select a cluster head and maintain cluster stability. Cluster heads collect packets from member nodes and throw away the ones that are not required. This results in the network using less energy overall. The clustering method that leverages swarm intelligence also monitors energy utilization in real-time. This allows the cluster head's functions to be switched around to maintain even energy use across all nodes. This strategy enables the network to be limited in resources, yet energy-efficient, long-lasting, and more effective at sending data. This makes the network an excellent choice for sensing scenarios when resources are limited. Below is the pseudocode for the proposed work.

PSEUDOCODE

1. Initialize all sensor nodes with energy, position, and neighbor information
2. For each round, do
3. Evaluate residual energy and node density for all nodes
4. Apply the swarm intelligence rule to select optimal Cluster Heads (CHs)
5. Form clusters by assigning nearby nodes to the selected CHs
6. Perform data sensing and aggregation at cluster heads
7. Compute energy-aware cost function for possible routing paths
8. Select optimal next-hop or base station using minimum cost criteria
9. Transmit aggregated data and update node energy levels
10. End round when all data is delivered, or energy threshold is reached

3.4. Energy-Aware Routing Mechanism

The energy-aware routing algorithm's goal is to find the optimal paths for cluster heads to communicate with the base station, thereby minimizing the energy expenditure. The leader of each cluster examines the available forwarding nodes and selects the one to use based on its remaining energy, communication costs, and distance from the base station. Swarm intelligence controls the routing process, and each node in the network functions as an agent that communicates with its neighbors to identify the best routes. The nodes exchange local energy and positional data with their adjacent nodes, enabling them to make decisions about routes in a decentralized manner. A cost function is implemented to decide whether a node should be forwarded or not based on such aspects as left energy, hops to the destination, and the reliability of a link.

The optimal course is the one with higher cumulative energy efficiency and which avoids the risk of overloading low-energy nodes and also prevents premature node failures. The algorithm is dynamic and evolves as the network changes, re-evaluating routes periodically to consider energy depletion or node dormancy. Additionally, aggregating information at middle nodes also reduces many unnecessary transmissions, thereby saving energy in the network. This approach balances the network's energy use and lifespan by evenly distributing the traffic across all its nodes. According to simulation findings, applying swarm intelligence to energy-aware routing has led to improvement of packet delivery ratio, control overhead, and steady throughput with different network conditions. With a mix of local interaction and global network targets, the energy-conscious routing mechanism offers a highly viable and scalable solution to the energy-limited WSNs, ensuring effective communication as well as a reliable solution in a decentralized system.

3.5. Adaptive Path Selection Strategy

The adaptive path selection strategy enhances the routing process by dynamically selecting routes based on network conditions, node energy, and communication cost. Every sensor node looks at a number of possible pathways to the base station and gives each one a fitness score depending on the amount of energy left, the number of hops, and the quality of the connection. Swarm intelligence concepts enable nodes to locally optimize their path choices by actively rewarding good paths and eliminating poor ones. Nodes keep track of their neighbors, checking their energy levels and connectivity, and update routes on the fly to prevent energy-starved nodes and minimize packet loss.

The strategy will leverage the inputs of previous transmissions, and hence, the system will adapt to the network changes in topology and prevent bottlenecks or congestion. The local node decisions combined with the collection swarm behavior provide the network with the optimal distribution of the traffic, whereby no node is required to work unnecessarily hard. The aggregation of data is applied to the selected paths to minimize transmission volume, which also helps save on energy expenses. The adaptive mechanism also handles load balancing between cluster heads and redistributes forwarding duties to extend the network's lifetime. Path selection can be adapted using swarm intelligence, allowing the algorithm to converge within a short time frame. This enables effective and reliable communication through the path selection process with minimal control overhead. It maintains data movement in dynamic settings as well as the strength of the vital nodes, and thus it is effective for large-scale and resource-constrained WSN applications.

3.6. Algorithm Workflow and Pseudocode

The first step in the algorithm process is network initialization. This is when sensor nodes are deployed, and each node determines its remaining energy and identifies its neighbors. The swarm intelligence-based clustering process is then implemented, and the nodes communicate to select cluster heads based on their energy content and the network topology. Member nodes identify themselves with the nearest cluster head after the cluster is created, resulting in a top-down communication structure. Data sensing of data is done at specified time intervals, and sensed data is transmitted by the member nodes to their cluster heads. The data aggregation is conducted by cluster heads in such a way that it reduces the load on transmission and afterwards transmits packets to the base station.

The energy-conscious routing algorithm selects forwarding nodes using the fitness measure that considers the remaining energy, the distance, and the communication cost. Local information is exchanged through nodes in an iterative process that refines in a decentralized fashion (like swarm behavior). According to the adaptive path selection strategy, the state of the network is continuously monitored, with routes being changed where necessary to prevent wasted nodes and to allocate traffic to network nodes. Control messages are maintained to the bare minimum to avoid an excessive amount of overhead with no compromises in the proper routing decisions. The workflow is represented in pseudocode as follows: initialization, cluster creation, data aggregation, routing computation based on energy requirements, adaptive path refinement, and periodic re-examination of cluster heads and paths. The swarm-based algorithm is iterative and guarantees convergence to energy-efficient routes without sacrificing network reliability. This systematic solution enables the network to achieve balanced energy consumption, a longer lifetime, a high packet delivery ratio, and reduced control overhead, as it is practically and potentially scalable for providing energy-constrained wireless sensor networks.

4. Results

The proposed energy-efficient routing algorithm was tested on a modeling dataset of a Wireless Sensor Network (WSN) that consisted of a homogeneous network of 100 sensor nodes randomly distributed over a 500m x 500m field. The initial energy of all nodes is 2 Joules, and the base station is located in the center of the network. Table 1 lists the data and simulation parameters that are to be assessed. The network lifetime versus the number of rounds is represented in Figures 4 and 5, which show the remaining energy per round. Figure 6 depicts the packet delivery ratio vs simulation rounds.

Table 1. Dataset and simulation parameters

Parameter	Value
Number of nodes	100
Network area	500 × 500 m²
Initial node energy	2 J
Base station location	Center (250,250)
Packet size	4000 bits
Transmission energy model	First-order radio model
Simulation rounds	1000

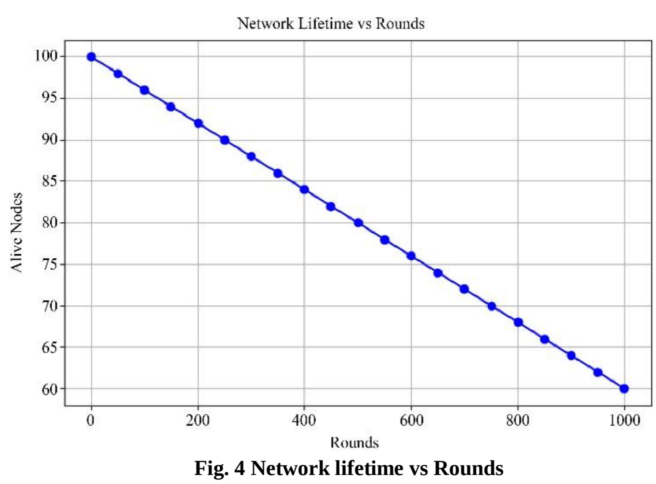

Fig. 4 Network lifetime vs Rounds

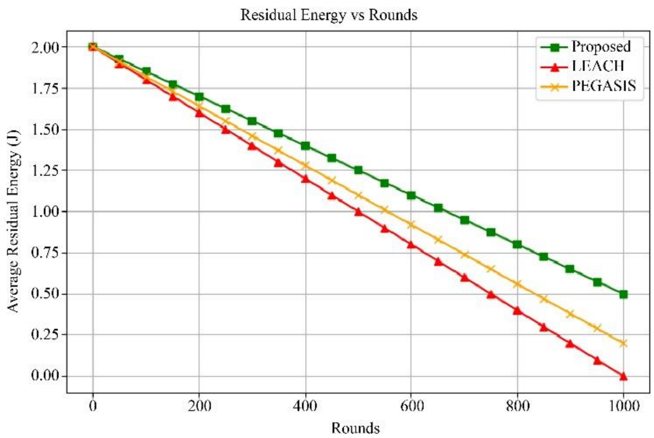

Fig. 5 Energy of residual vs Rounds

The network was simulated to execute 1000 rounds, with each round constituting a sense and forwarding round of data. In the simulation, the positions of nodes, the energy of nodes, and the distances of communication were recorded. The aggregation of data by the cluster head reduces the number of packets that have to be sent. The parameters of the network, including simulation (node density), transmission range (4000 bits), and energy constraints, had to be documented to ensure optimal performance. The proposed method was evaluated based on performance, particularly using the following key output measurements: Network Lifetime, Packet Delivery Ratio (PDR) from Equation (1),

$$PDR = \left(\frac{Total\ packets\ received}{Total\ packets\ sent}\right) * 100 \quad (1)$$

Table 2. Output metrics

Metric	Value
Network Lifetime (rounds)	850
Packet Delivery Ratio (%)	96
Throughput (kbps)	410
Energy Consumption (J)	1.22

Throughput and Energy Consumption. Network Lifetime is the time period during which the initial node will run out of energy. The share of packets received at the base station among those sent is referred to as the PDR. Throughput is a measure of the data being given out at any one unit time, and energy use is a measure of the sum of the energy used by all the nodes in a given round. Swarm intelligence development yields a routing algorithm that ensures the network achieves balanced energy consumption through the dynamic rotation of cluster heads and the energy-conscious selection of paths. The average values were obtained after 1000 rounds, as shown in Table 2, where better results were obtained as compared to the application of the flat and hierarchical routing methods. The algorithm offers a better network lifespan, reduced energy consumption, and constant throughput, which proves its effectiveness in energy-sensitive swarm intelligence, simplifying WSN communication. It was compared to the swarm intelligence routing algorithm proposed alongside other routing algorithms, including Low-Energy Adaptive Clustering Hierarchy (LEACH) and Power-Efficient Gathering in Sensor Information Systems (PEGASIS). Comparable measures are Network lifetime, packet delivery ratio, throughput, and energy consumption. Table 3 presents a side-by-side analysis, showing that the traditional protocols are less efficient than the suggested method in terms of network longevity and energy consumption.

Table 3. Comparison of proposed and existing methods

Metric	LEACH	PEGASIS	Proposed Method
Network Lifetime (rounds)	620	700	850
Packet Delivery Ratio (%)	88	91	96
Throughput (kbps)	350	380	410
Energy Consumption (J)	1.85	1.45	1.22

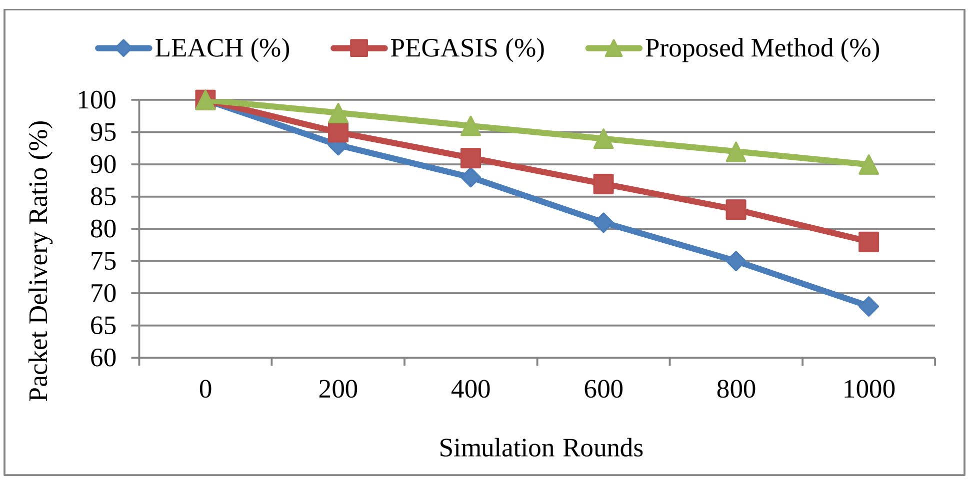

Fig. 6 Packet delivery ratio vs Simulation rounds

Adaptive cluster head selection, combined with energy-aware path selection, allows for more consistent energy use, resulting in fewer nodes being killed in early rounds. The swarm-based method also reduces control overhead and is very reliable. The simulation outcomes validate the hypothesis that the proposed algorithm enhances packet delivery, throughput, and operational life cycle, making it effectively applicable in an energy-limited WSN setup.

5. Conclusion

The paper introduces an energy-efficient routing algorithm based on the swarm intelligence of Wireless Sensor Networks, with a focus on adaptive clustering and energy-conscious path selection. The strategy ensures a balanced use of power, a long network lifetime, reliable data delivery, and low control overhead. Experiments with simulation show that the protocol dramatically increases network lifetime, packet delivery ratio, throughput, and minimizes energy consumption in contrast to other traditional protocols, such as LEACH and PEGASIS. The proposed strategy supports a dynamic reaction to variations in node energies and network topology by devolving decision-making and carrying out iterative optimization processes, based on swarm behavioral principles. The algorithm is highly scalable and has a strong ability to be used in large-scale and resource-constrained WSN deployments, which gives the algorithm a viable framework that can be transferred to the real world. This solution to heterogeneous networks and mobility-aware optimization can be further explored to achieve increased energy efficiency and enhanced communication reliability.

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