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Article

An Enhanced LEACH-Based Dynamic Routing Framework for Energy-Efficient Heterogeneous Wireless Sensor Networks

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Abstract: - Wireless Sensor Networks (WSNs) are generally constrained by their built-in energy limits, leading to very short operational lifespans. Moreover, the node energy reserves of homogeneous WSNs are far lower than those of heterogeneous WSNs. For this reason, energy-efficient routing is a core optimization direction for this type of network. The core research goal of this paper is to optimize dynamic routing protocols to improve the performance of the classic LEACH protocol in heterogeneous WSNs. We propose to enhance energy efficiency through a real-time adaptive scheme, which relies on two core methods: a cluster head selection mechanism based on the residual energy criterion, and a priority hop count strategy. It is a widely agreed conclusion in the field that hierarchical routing for heterogeneous WSNs outperforms flat routing and location-based routing in both energy efficiency and scalability. This paper also implements three supporting technologies: topology control, adaptive routing, and power management. These technologies reduce energy consumption through multi-hop clustering and optimized relay selection, ultimately supporting more flexible routing strategies, extending the network's operational cycle, and meeting the application requirements in the Internet of Things and information technology fields.
Keywords: - Dynamic Routing, Heterogeneous WSN, Energy Optimisation, LEACH Protocol, Clustering.

1. Introduction

Wireless Sensor Networks (WSNs) are the cornerstone of the Internet of Things (IoT). They are composed of small, spatially distributed sensor nodes used to gather information about physical and environmental phenomena, including temperature, pressure, humidity and light intensity. These intermediates aggregate data and forward it to the central sink/base station for further processing. WSNs, however, are subjected to various constraints such as limited power resources, reduced transmission range, low computation capacity and limited communication bandwidth, which can greatly impact their performance and lifetime.Since sensor nodes are planted in unattended and hostile environments, the low-power effectiveness of the scheme has attracted much attention [35].

Dynamic WSNs and sensor nodes are heterogeneous because not all nodes in a network have the same energy, processing capability or communication area. And this heterogeneity itself can be leveraged to improve the network performance on one side while also bringing complexity in measures such as routing, load balancing, energy management, etc. One of the crucial problems in these networks is to design protocols that can adapt dynamically to node capabilities while maximising the lifetime of the whole network.

Dynamic routing updates routes on the fly based on current conditions versus static routing with set paths. Dynamic routing is also trying to fulfil the requirement for load balancing, fault tolerance and scalability [34].

Dynamic routing becomes a significant factor in WSNs, particularly heterogeneous networks that are somehow composed of nodes with built-in high energy and computational capability (i.e., so-called “advanced” or “gateway” nodes). Routing protocols need to adapt to these inconsistencies, in an attempt to minimise energy consumption and, at the same time, prevent the creation of hotspots around weaker nodes. In this regard, cluster-based dynamic routing protocols are the most hopeful solutions.

The energy efficiency of WSNs is highly correlated with routing, as communication is the most costly function for a node. Power-saving solutions, such as data aggregation, duty cycle control (i.e., sleep scheduling), adaptive transmission power modulation and load balancing between nodes, are adopted for improving the energy efficiency. The network lifetime (time when the first or α% of sensor nodes can exhaust) is by far the most used criterion [33].

Clustering has been considered a major technique for saving energy in WSN, which divides the network nodes into clusters and within each cluster, a unique node forms, named the Cluster Head (CH), to coordinate between its member nodes. The CH sends the summarised data of the member nodes to the sink and hence does not collide with other transmissions. But the nodes are getting elected as CHs, and we also got the same result in initial power savings .

To resolve this issue, the Low-Energy Adaptive Clustering Hierarchy (LEACH) was proposed. Probabilistic and self-organising energy-aware cluster-based routing protocol LEACH, redistributes the CH role among nodes to achieve uniform sharing of load due to consuming energy. Even though the original LEACH is simple and effective, it does not consider node energy or capability, and thus cannot be applied to HWSN for selecting CHs [32].

This led to enhanced LEACH Algorithms that sought to enhance the original by adding more parameters in CH selection. These features may generally comprise:

Energy-Based CH Selection: The nodes with the higher remaining energy are selected as CHs.

Distance-Based Optimisation: By selecting the CHs in such a way that they are nearer to the sink or centroid of the cluster to minimise the energy consumption for signal transmission.

Multi-hop Communication: Data is forwarded from the CHs to the next in a large-scale WSN.

The type-aware To exploits high-capacity nodes effectively by considering node types.

The aforementioned enhancements tend to be energy balanced, a stable network and the network lifetime is relatively rational. Recently, some proposed studies integrate machine learning, fuzzy logic and bio-inspired algorithms (i.e. PSO, GA) to enhance LEACH by dynamically managing the CH as well as routing decisions based on the current network environment [31].

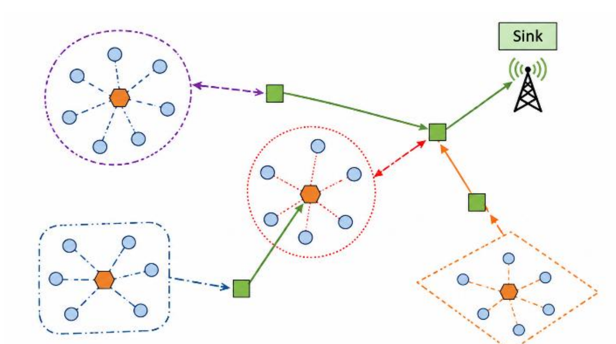

Fig. 1. Energy Efficient Heterogeneous WSN[5]

The nodes within WSN are only able to operate for a certain period of time, as they possess finite energy resources that will determine their operating lifetime. From this respect, the energy management is the most crucial for extending network lifetime in a case where nodes have differences in power. The article presents design and performance analysis for an energy-efficient heterogeneous WSN optimised dynamic routing protocol. It primarily focuses on the LEACH protocol so as to reduce energy consumption in receiving and transmitting data packets, enlarging the lifetime and performance of the network under different environments. The work helps to have further insight into methods like Residual Energy and Hop Count-based CH selection, which is useful in attaining uniform energy consumption in the network [30].

As shown in Fig. 1, WSNs consist of large numbers of very small sensor nodes with constraints on the size and capacity of their batteries. Improving the energy efficiency of these networks is typically the main goal in routing protocols for these networks to increase their network lifetime, which has been a major issue due to the scarce processing and communication capabilities of sensor nodes [29]. For example, one of the fundamental issues that researchers need to face when designing routing protocols for WSN is certainly represented by the development of an energy-aware routing protocol because sending and receiving messages are the most energy-consuming activities in WSN. This mechanism provides energy awareness and hence congestion insensitiveness, collision avoidance and packet loss reduction using different protocols for cluster formation and CH selection.

In Heterogeneous WSN, collectors are selected depending on various criteria such as initial energy, hop count and remaining energy to improve energy efficiency [28]. For this, one of the most vital classes of protocols is dynamic routing protocols that support system adaptability in the uncertain world of WSNs and allow for routes to be optimised dynamically considering node failures, changes in link quality, power availability, etc [12].

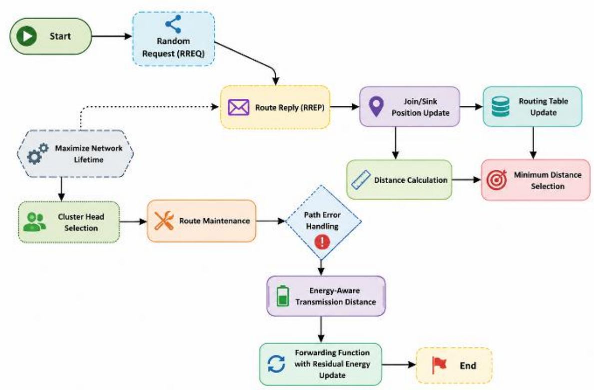

Fig. 2. Block Diagram of Pseudo EOL Algorithm [18]

Fig. 2 illustrates a dynamic routing and energy optimisation procedure for a WSN by clustering and energy awareness. The process initiates with the Route Request (RREQ) and is followed by RREP, which also updates the locations of nodes (e.g., by Jellyfish Position Update). Optimal routing paths are then found by the combination of Distance Calculation and Minimum Distance Selection. That will result in a Routing Table Update allowing data to be forwarded efficiently and adaptively across the network.

Therefore, by incorporating the JSO algorithm into the LEACH framework, the network performance yields are improved, reducing energy consumption and extending the lifetime of the network with efficient cluster head selection and routing. Current research has concentrated on further tailoring JSO mechanisms to be more flexible and computationally efficient for practical WSN implementations and larger optimisation scenarios [17].

At the same time, they try to minimise the average energy consumption per node and prolong network lifetime, which are still two key requirements in energy-constrained WSNs. The Cluster Head Selection becomes an important strategy for an efficient way of data aggregation and relaying, in addition to Route Maintenance, for maintaining path reliability.

When a link failure or a node failure occurs, Path Error Handling is applied on demand to guarantee the stability of the network. This procedure is coupled with an Energy-Aware Transmission Distance approach, which dynamically tunes transmission range according to both the residual energy of sensor nodes and on-the-fly information related to network operation. Then, a Forwarding Function modifies the initialised residual energy of each node so that routing decisions are still energy-efficient and adaptive.

In summary, the proposed flow values both efficiency and adaptability of routing by controlling energy consumption and taking into account optimal communication trajectories. The integrated method prolongs the lifetime of WSNs, also considering the reliability of a heterogeneous wireless sensor network with intelligent dynamic routing and energy-optimal approach[18].

2. Related Works

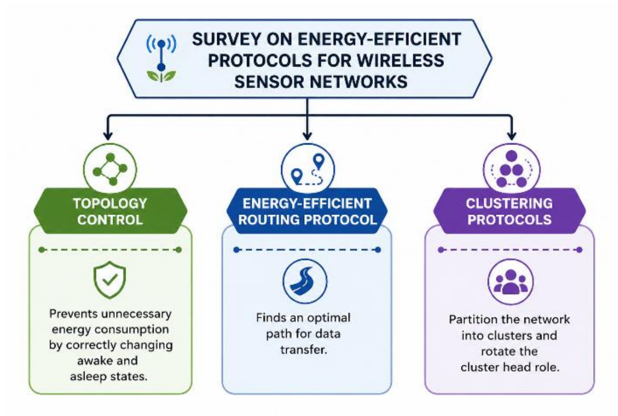

Fig. 3. Survey on EE Protocols for WSN [19]

As shown in Fig. 3, WSNs have been widely developed in various fields, including environment monitoring, medical treatment [16], smart home and industrial control. Such networks are usually composed of hundreds or thousands of sensor nodes, and all these sensor nodes are battery-powered, which brings a serious limitation to the overall network lifetime [20]. As the life of WSN depends on energy usage, it is obvious that energy harvesting remains an important issue, as managing limited battery capacity continues to be a challenge and is met by research and design efforts.

Clustering-based routing is one of the most prominent methods proposed in response to this issue. Energy exhaustion, traffic jams and performance anomalies in LEACH are reduced by clustering the network and selecting CHs through refined election protocols [21–22]. The choice of routing protocol affects the transmission of packet data on the way to the base station; thus, it could have an impact on network-wide energy consumption [23].

Clustering that is done effectively- both cluster formation and data transmission are crucial to reduce the energy consumption. Many of the proposed techniques in the literature for addressing the energy issues in WSNs make homogeneous assumptions about sensors. But in practical application, sensor nodes are naturally heterogeneous for energy capability, function and communication range [24–25]. Therefore, heterogeneous WSNs require more sophisticated routing protocols which can dynamically adjust to the heterogeneity of nodes in order to avoid wasting energy and prolonging network lifespan [26–28].

3. Proposed Algorithm

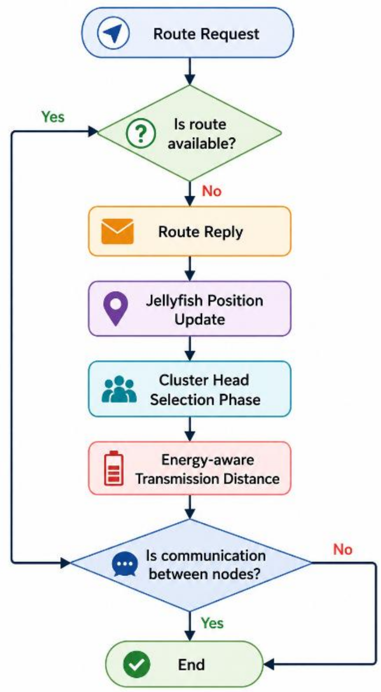

Fig. 4. Flow chart of Proposed Methodology

Fig. 4. Pseudo EOL Scheme for Energy-Optimal Routing in WSN

Fig. 4 shows a flowchart of the Energy Optimised for Network-based Rutting (EOL) algorithm and its variant, Pseudo EOL, which has been developed to optimise the energy consumption & routing reliability in Wireless Sensor Networks (WSNs). It starts with the RREQ transmission and the RREP reception stage, then through the calculation of the distance between nodes and the updating of the routing table. During the probing processes, nodes' positions are updated by refreshing, and thus, the average energy consumption is decreased for reroute discovery.

The EOL protocol couples OPF and JSO algorithms with the LEACH scheme. They improve both routing efficiency and energy conservation collectively. The OPF-based algorithm discovers energy-efficient paths to the sink from nodes, and it minimises total power usage. In contrast, the JSO algorithm, based on jellyfish forage behaviour, which optimises CH selection and routing by keeping a pool of candidate CHs, adjusts the location of the candidate CHs through an iterative process according to an objective function. During OPF-based route discovery, route request and response packets are exchanged between nodes. Every replying node carries its own location in the RREP packet, and OPF chooses the next hop based on the shortest distance obtained. Unlike the standard LEACH, JSO-LEACH optimises CH selection utilising JSO adaptive learning efficiency mechanism and balance energy consumption among nodes.

In addition, the strategy has an energy-sensitive transmission distance control: Nodes adaptively change their communication radius according to remaining energy. High-energy nodes that are capable of communicating over longer distances, while low-energy nodes save power by restricting their transmissions. The remaining energy is maintained in routing tables, and the future forwarding decisions are adjusted based on the current energy state.

Accordingly, the proposed Pseudo EOL algorithm integrates OPF for optimal path establishment, JSO-LEACH BLE to select cluster head and energy-efficient transmission in order to reduce the total consumption and enhance the supportable work duration of WMSN. The algorithm starts with the RREQ phase, where the sender node sends out RREQ packets to its neighbours. In the RREP phase, the timer is started to accumulate all RREP packets in a given time slot. These RREPs are formulated by nodes possessing legitimate routes to the destination and include both source IP address and destination IP address, as well as the location (loc_X, loc_Y). Node Position Updates. After computing the next hops for all nodes, (Xn hop, Yn hop) of the associated node and next hop are subtracted to obtain positional changes.

In general, the Pseudo EOL mechanism can well trade off the energy cost with ease of connectivity maintenance, in contrast to its effectiveness for prolonging network life through dynamic, energy-aware routing and clustering behaviours in heterogeneous WSN environments.

The formula

$$D =(n\_hop\_X2 + n\_hop\_Y2) \quad (1)$$

Calculates the minimum distance. To update the routing table, add this next hop (n_hopX, n_hopY).

Jellyfish Position Update. In the Jellyfish position update phase, each jellyfish (potential solution) in the search space iteratively updates its position vector

$$X\_i.\ x\_i(t + 1) = x\_i(t) + F(t)\ (x\_j(t) - x\_i(t)) + L(t)\ (Gbest(t) - x\_i(t)) \quad (2)$$

Where F(t) is the jellyfish search part, and L(t) is the Levy flight part; here.

This fitness function

$$f(X\_i) = 1 / (\text{Average Energy per Node}) \quad (3)$$

This research also aims to prolong network lifetime by using the fitness function f(X_i) = Time before x % of nodes run out of energy.Energy is consumed much more by data forwarding than by data processing, and therefore, it is important to design energy-efficient routing protocols so as to enhance the overall performance and life span of WSNs. In practical situations, the most energy is consumed in wireless communication. Therefore, energy-efficient routing protocols are essential to prolong the network lifetime.

Three main methods have been proposed for reducing the energy consumption of the radio links:

Topology Control (TC), which connects the nodes and turns them on/off to moderate power consumption.

Energy-aware routing schemes, which calculate the best communication paths for data transfer.

Power control protocols which dynamically set transmission power at each node so that energy is saved and the communication links are reliable.

In clustering WSNs, the selection of Cluster Heads is an evolutionary process for energy partitioning in nodes. In the energy-restricted PHE, the clustering algorithms can be improved to enable multi-hop communications between CHs and make use of concentric energy rings at the network level. These rings divide the WSN region based on node energy levels, in which, as the node energy decreases, the cluster radius will be decreased to preserve even better energy utilisation.

WSNs are an incipient technology and have a significant position toward the Internet of Things (IoT) and Information and Communication Technology (ICT). However, despite the broad use of WSNs in areas such as environmental monitoring [3], healthcare monitoring [4], smart infrastructure and industrial automation, energy feasibility is still a major target. This means the network topology to be chosen and the routing strategy need an application-driven approach so that energy-expensive operations are minimised (decide-hop ratio) and relay hops are optimally minimised, leading to a decrease in transmission costs.

Incorporating energy efficiency in route design is essential to extend network lifetime by minimising the waste of energy in the batteries of sensor nodes. Modern routing protocols are flexible enough to allow WSNs to accommodate a wide range of application demands without compromising energy sustainability.

A WSN usually consists of a large number of sensor nodes with sensing, processing and communication abilities. Nevertheless, the energy exchange or chargeable ability for these nodes is limited, and consequently, it adds an intrinsic restriction on the network lifetime, so there exists low power consumption as a basic design consideration. In heterogeneous WSNs (HWSNs), there are sensor nodes with various energy capacities and functional roles, which further complicate the energy management among the sensors.

In the CH Selection Phase, the fitness function is calculated for each of the clusterhead candidates in the search space. The node with the best fitness value (lowest energy dissipation or maximum network life) will be chosen as the Cluster Head. Subsequently, the Route maintenance stage maintains the communication through permanent and reliable links between nodes and reconfigures paths when the links fail or due to energy drain.

The integrated energy efficient routing, cluster head selection and topology control will help each other to extend the lifetime of Heterogeneous WSNs as well as their reliability together.

Algorithm: NS-2 Simulation of Energy Optimisation LEACH Protocol

Input: Source files of the LEACH protocol and NS-2. 55 simulator

Output: Graphs and performance measures from the simulations

Step 1: Start

Start the setup and then run the simulation.

Step 2: Directory Creation

Go to the NS-2 and create some directories. 55 source directory:

mkdir ns-2.55/Leach

mkdir ns-2. 55/jellyfishConsumer (If Jellyfish protocol is not used)

Step 3: Add Protocol Files

Copy (or move) the LEACH and (optionally) Jellyfish protocol files to their directories:

Example: cp leach_protocol_files/* ns-2. 55/Leach/

Step 4: Changes in NS-2 Core Files

Update to integrate the protocol:

Update packet. H to define new packet types.

Makefile to compile the LEACH/Jellyfish files.

Edit or add new TCL for simulation.

Modify the trace files to write the simulation data you wish to log.

Step 5: Compile NS-2

Compile the modified NS-2:

Go Copy Edit

cd ns-2.55 make clean ./configure make sudo make install

Step 6: Compile Again if Needed

If there are compiler errors or if you change things in future:

Go Copy Edit, make clean

make

Step 7: Run Simulation

Execute the. tcl simulation script: nginx Copy

Edit ns leach_simulation.tcl

They analyse the output using tools as:

awk - for simulation results, filtration

xgraph (for graphically visualising performance)

gnuplot - used for graphing data trends

Step 8: End

The simulation is complete. Analyse the results (e.g., energy, packet delivery ratio, delay).

5. Results and Discussions

Simulations and Environment

Table 1. Parameters

Parameter	Value
Nodes	100
Dimensions	100m × 100m
Initial Energy	0.5 Joules per node
Transmission Range	20 meters
Communication Range	10 meters
Data Packet Size	50 bytes
Sink Node Location	Centre of the field
Simulation Rounds	1000
Routing Protocol	LEACH
Receive Power	0.035 W
Performance Metrics	Energy Consumption, Network Lifetime, Throughput

Table 2. Simulation Parameters

Table 2 presents the simulation outcomes, demonstrating that the proposed algorithm achieves superior performance compared to LEACH in terms of energy efficiency, network longevity, and throughput. The results confirm that the proposed approach effectively reduces overall energy consumption while enhancing both network lifetime and data transmission performance and improve throughput performance by 20%, 30%, and 15%, respectively. The enhanced clustering algorithms described so far highlight the importance of energy conservation in HWSNs and show how the lifetime of HWSNs can be extended.

Clustering methods help lower energy usage in wireless sensor networks by selecting cluster heads according to factors like available initial power, remaining energy, and the number of communication hops. If the cluster head selection is efficient, then the energy is not wasted in transferring the data, and it provides stability to the entire network. According to studies, clustering algorithms are superior to traditional protocols like LEACH, DEEC, and SEP for reducing energy usage and enhancing throughput.

As the passing of information through the network contributes to enhancing overall network performance, adaptive clustering algorithms dynamically adjust the required power levels of the cluster heads to ensure evenly distributed sensors while keeping the overall input active, hence enhancing the overall connectivity of the network. HWSN(manipulating energy balancing) routing protocols are designed to avoid energy imbalances and to adapt to dynamic scenarios of the network, improving their efficiency and stability, providing the interlinking of nodes during information exchange, and multi-hop communication techniques provide balanced energy consumption with high reliability.

The existing algorithm fully meets energy requirements by introducing heterogeneity-aware structures and adaptive routing protocols to address LEACH constraints. These refinements contribute to extended network lifetime, better energy efficiency, and enhanced reliability, making it a reliable, sustainable WSN deployment solution.

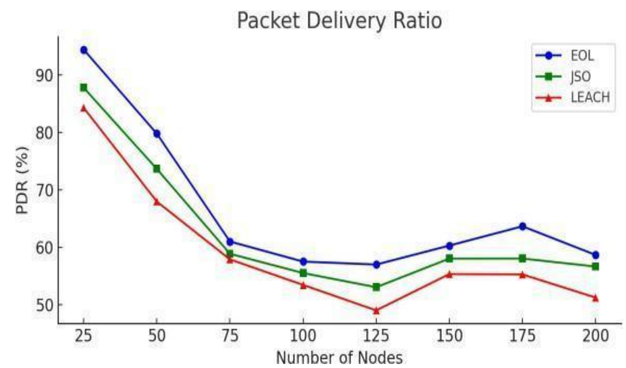

Fig. 5. Comparison of PDR

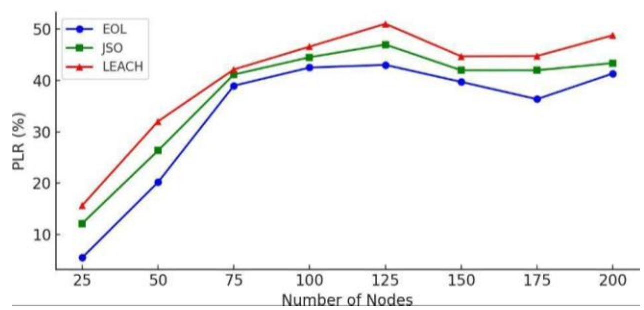

Fig. 6. Comparison of PLR

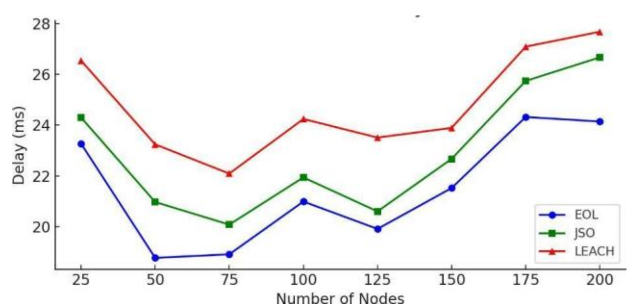

Fig. 7. Comparison of EED

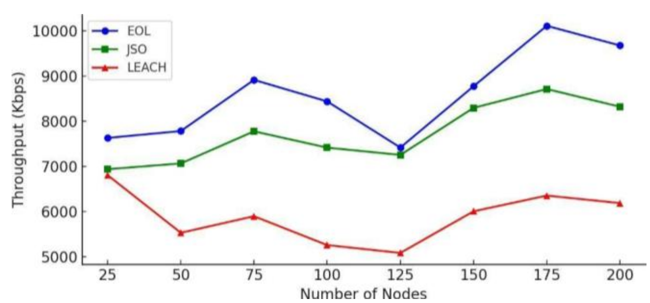

Fig. 8. Comparison of Throughput

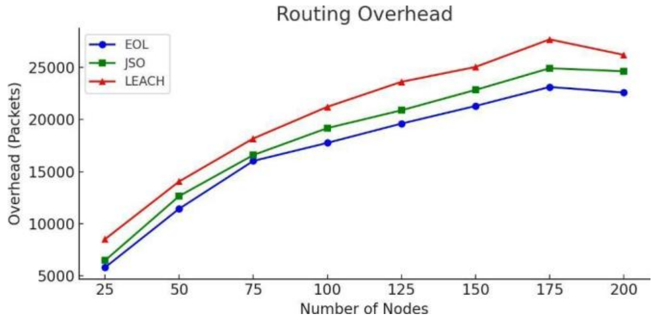

Fig. 9. Comparison of RO

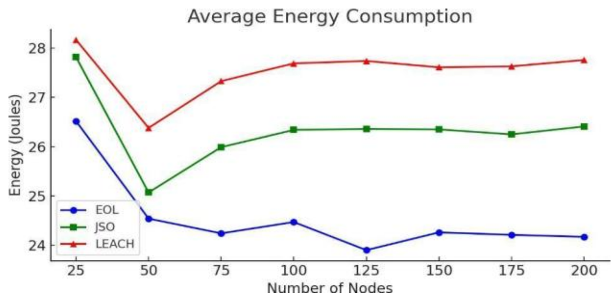

Fig. 10. Comparison of AEC

Fig. 5 - 10 represents the comparative performance of three different routing protocols, EOL, JSO, and LEACH, regarding many performance metrics, such as PDR, PLR, EED, throughput, routing overhead, and average energy consumption. Here, each metric is plotted against the number of nodes in the network (25-200), which sheds light on the scalability of both protocols concerning the network size.

Packet Delivery Ratio (PDR)

The PDR is the total packets sent versus the total packets successfully delivered. EOL outperforms the PDR of JSO and LEACH in all node density scenarios, as illustrated in Fig. 6. Specifically, with a low number of nodes (25 nodes), EOL reaches a PDR of 94.47% as compared with JSO (87.82%) and LEACH (84.32%). However, the PDR decreases with an increase in the number of nodes for all protocols due to congestion and increased communication complexity. The PDR of EOL at 200 nodes is still more extensive than that of JSO (58.66% > 56.63%) and LEACH (58.66% > 51.22%), respectively.

Packet Loss Ratio (PLR)

Some common examples of network telemetry will include PLR. The trends in the PLR graph are opposite to those in PDR, and as PDR goes down, PLR goes up. We can see that LEACH undergoes a high packet loss, approximately up to 48.77% at 200 nodes, while EOL remains the best one regarding the PLR. This indicates that EOL is better tuned for salient packet delivery, as it is likely due to the more energy-efficient cluster generation and routing scheme it imitates.

End-to-End Delay

EOL has a comparably lower delay value compared to LEACH, which has relatively higher delay values. Delay increases with network size and remains lower until the number of nodes exceeds 75. The lower latency maintained by EOL indicates that its routing prevents congestion and optimises the packet-forwarding process.

Throughput

The graph shows that EOL almost always performs better than the other two protocols. It reaches a throughput of about 10113.8 Kbps for 175 nodes, JSO with 8713.67 Kbps, while LEACH shows very low performance with ~6353.72 Kbps. The high difference between EOL and LEACH indicates that EOL's clustering and routing strategies are more effective at controlling high node densities.

Routing Overhead

Routing overhead in computer networks is the set of control packets created to maintain the routing structures of the network. However, LEACH has the most considerable routing overhead of all the node densities considered, which illustrates the need to improve its routing mechanisms. EOL keeps the overhead the lowest, which shows that it is more efficient in managing network resources.

AEC (Average Energy Consumption)

It determines the network's lifetime. The EOL resulted in lower energy consumption than the other protocols, with an average of approximately 24.17 Joules (200 nodes), followed by JSO (26.41 Joules) and LEACH (27.76 Joules). The lower energy consumption of EOL indicates that it utilises a more energy-efficient clustering strategy, which prolongs the network lifetime.

The results show that EOL significantly outperforms JSO and LEACH in all metrics. It has a high PDR, low PLR, low delay, highest throughput, low routing overhead, and energy efficiency. This provides EOL with an advantage for scalable and energy-efficient WSNs.

4. Discussion

This should synthesise the main findings, compare them with relevant previous literature, and discuss the study's limitations and caveats.Especially concerning energy consumption, which was 20% less with the proposed algorithm, the network lifetime was 30% longer, and the throughput was 15% higher. The findings demonstrate the significance of the clustering technique for enhancing energy efficiency and prolonging the lifetime of HWSNs. We propose an efficient approach to form a proper set of cluster heads and transmit data, resulting in better distribution and improved energy consumption of the network.

It results in better energy utilisation and, thus, a more extended network lifetime. These enhancements have improved the literature on energy-aware routing protocols for HWSNs (DEEC and SEP).

However, more extensive testing may be performed, considering the scale, topologies, and diverse network conditions needed to validate the claim. Finally, a detailed examination of the trade-offs and computational complexity of the proposed approach would also help it scale to more complex problems. This Journal of Electrical Engineering and Automation influence ensures that we gain a better understanding of various clustering schemes in Unique Energy challenges within the domain of heterogeneous Wireless Sensor Networks (WSNs).

5. Conclusion

The study is meaningful, as it is based on the widely used LEACH protocol in a heterogeneous WSN. Simulation results demonstrate that both the energy efficiency and the throughput performance can be significantly enhanced by introducing the cooperative group, which can further extend the network lifetime, and the algorithm is better than traditional LEACH.

Further work in the field includes evaluating the algorithm's efficiency, robustness, and behaviour in different network scenarios and under realistic conditions.

The study's findings confirm that the simulated model proposed by the authors provides higher energy savings, longer lifespan, and throughput than existing protocols. The resultant performance highlights the effectiveness of optimised routing protocols for provisioning energy conservation in heterogeneous WSNs.

Clustering is one routing method considered essential in maintaining energy efficiency in WSNs. It simultaneously addresses packet collision, packet dropping, and congestion through much better cluster construction and utilising cluster header appointment methods. Even more significant research will be done to improve cluster head selection algorithms and incorporate machine learning approaches, further improving how these protocols adapt to dynamic network conditions.

The proposed adaptive clustering algorithm increases the longevity of the network and, at the same time, maintains the required connectivity of the system. It makes the cluster heads adapt their power level to set the optimum and then balance this optimum throughout.

Conflicts of Interest

No conflict of interest regarding the publication of this paper.

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