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Routing Protocols for Enhanced Energy Efficiency in Wireless Sensor Networks

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Abstract:

The rapid progress made on wireless sensor networks (WSNs) has created a necessity for effective and energy efficient routing protocols that can be beneficial with respect to energy consumption. Efficiency of energy usage especially in the WSNs has always proven to be a tough nut to crack because the sensor nodes have constrained batteries and extended periods of network operation is preferable. This work deals with the assessment and comparison of five well-known routing protocols i.e. Low Energy Adaptive Clustering Hierarchy (LEACH), Power Efficient Gathering in Sensor Information System (PEGASIS), Threshold sensitive Energy Efficient Sensor Network (TEEN), Geographic and Energy Aware Routing (GEAR) and a new Hybrid Protocol on several performance measures aimed at investigating the performance of the protocols in improving energy efficiency.

In this study, a network area measuring 100m x 100m with 100 static sensor nodes randomly deployed is designed and simulated. The simulation tool employed in this analysis is MATLAB which offers a platform to gain and test each protocol under the same network circumstances without any modifications. The main performance parameters that were focused on include the overall duration of the network, the mean energy consumption for each round, the Packet Delivery Ratio PDR and the delays.

The results of this study suggest that the Hybrid Protocol will perform best in large scale WSN applications where it is necessary to have high data delivery efficiency with lower delays, and longer network life.

Key Words: Sensor Network, Low Energy Adaptive Clustering Hierarchy (LEACH), Power Efficient Gathering in Sensor Information System (PEGASIS), Threshold sensitive Energy Efficient Sensor Network (TEEN), Geographic and Energy Aware Routing (GEAR)

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1. Introduction:

Wireless sensor networks (WSN's) have appeared as one of the incredible evolution in technology over recent years to provide various services such as environmental monitoring, healthcare, military surveillance, and smart cities. In most cases, a WSN consists of a very large quantity of sensor nodes, which are small and low-cost devices that can individually sense and process the surrounding environment as well as transmit environmental data wirelessly to a listening post or hub. The most formidable problem in WSNs has to be that of power exhaustion of the sensor nodes. Since these nodes are sometimes used in extreme weather or geography, it becomes either problematic or outright impossible to change or charge the batteries. Therefore, energy efficiency becomes a severe issue in the design and the functioning of WSNs. [1]

Among the processes which consume a large amount of energy within WSNs is routing. This is the form used to send the information gathered from sensor nodes to the base stations. This is due to the fact that energy is wasted and routing is done poorly resulting into nodes using up their energy too fast and which will invariably affect the network's lifespan due to power constraints. Hence, developing routing algorithms which minimize the energy efficiency is a very important area of study.

Objectives of the Study:

The primary objective of this research is to provide a comprehensive review of energy-efficient routing protocols in Wireless Sensor Networks, focusing on the following key aspects:

- **Classification of Protocols**: Categorizing routing protocols into structures and hierarchical and location driven methodologies in detail.
- **Energy Efficiency Evaluation**: Involves assessing the performance of each protocol in terms of energy usage efficiency and its impact, on network longevity and scalability.
- **Comparison of Protocols**: To evaluate their strengths and weaknesses, for applications, in wireless sensor networks (WSN)
- **Identification of Research Gaps**: includes highlighting standpoints where there are still some issues and it's necessary to additional research in order to construct more energy efficient routing strategies.
- **Proposed Improvements**: Proposals that aim at improving the current standards or recommend potential future advanced protocols to be used with flexibility to cater for all dynamics of WSNs.

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Significance of Energy-Efficient Routing:

On the other hand, optimum routing enhances lifetime of network, increase performance and reliability of Wireless Sensor Networks (WSN) and prolongs network lifetime. Efficiently designed routing protocol can help reduce data transfer and eliminate energy intensive processes such as multi hoppy communication by equally distributing the energy usage within the network topology. A responsive management solution that would respond to sudden spike of workloads which may lead. [2]

Challenges in Energy-Efficient Routing:

Designing routing protocols that maximize energy efficiency in WSNs is a complex task due to several inherent challenges:

- **Node Heterogeneity**: In WSN applications the diversity of nodes such as sensor nodes of varied energy resources, different processing power, different transmitting power etc makes routing protocol design inapplicable for all configurations.

- **Dynamic Network Conditions**: WSNs operate in dynamic environment where the network topology may change frequently due to node mobility, node failure, or environmental events. Thus, it is important that the routing protocols be able to adapt to these changes.

- **Data Redundancy**: Sensor nodes in WSNs will generate redundant data very often especially where densely deployed networks are used. Wi-Fi-like energy savings are possible if the transmission of redundant information is minimized with efficient data aggregation techniques.

- **Scalability**: When the size of sensor node scales up, many routing protocols have difficulties over-head control due to large inflexibility [4]. A scalable protocol means one that works in relatively large networks, without the efficiency decreasing a lot in terms of energy consumption as well as communication overhead.

2. Related Work:

2.1. Hierarchical/Cluster-Based Routing Protocols

Hierarchical or cluster-based protocols have consistently remained a major focus of research, with their ability to reduce communication overhead by grouping nodes into clusters and assigning a cluster head for data aggregation and transmission. Recent studies have introduced several novel approaches to enhance their energy efficiency:

A. S. Ahmed et al. (2020) have come up with an improved version of the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol known as LEACH-MF (LEACH with Multi-hop Forwarding). The authors added multi-hop communication among the clusters in order to save

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energy. Simulation results showed that this technique has better performance compared to conventional LEACH protocols with respect to network lifetime especially in large scale WSNs. [1]

M. S. Alrabea et al. (2019) proposed extensions to the MLEACH based on multi-level approaches taking into consideration the different network diameters. Their result was primarily the categorization of cluster heads taking into consideration residual energy and node density such energy targeting saved a lot and increased the scalability of the networks. [2]

S. Kumar et al. (2021) have designed a mono-hybrid PEGASIS routing protocol augmented with Artificial Intelligence (AI), which can determine a suitable route, based on dynamic traffic conditions, and availability of the nodes' battery power. This integrated method aims to reduce the probability of head saturation and, thus prolong the duration of the network. [5]

M. Hussain (2022) extended the functioning of the TEEN protocol by proposing some enhancements for this protocol which utilises a standard static threshold. An active response to the changes of the environment is offered by this adaptive mechanism ensuring that energy consumption is kept at a low level even for event-driven networks where changes occur rapidly and can drain node energy. [6]

D. Zheng (2021) devised a fuzzy TEEN variant that proportions certain thresholds according to the environmental and traffic conditions, thus increasing both network performance and energy efficiency. [7]

2.2. Flat Routing Protocols

Over the years, flat routing protocols also improved. These protocols do not differentiate among nodes, so energy efficient routing is realized in flat networks via movement of data and multi hop communication enhancement techniques.

Gupta et al. (2020) concentrated specifically on enhancing flooding and gossiping protocols through intelligent data aggregation techniques. In their proposed prostate, l ow redundancy phenomena owing to transmission of similar data from the neighbouring nodes are observed that is helpful in conserving battery energy in case of dense networks. [8]

R. J. Kang et al. (2020) devised improvements for gossip-based routing and implement adaptation in terms of an approximate gossiping probability. This method also participates in the criterion of balancing the energy consumed by vectors as it seeks to vary the forwarding probability as per node energy levels and network traffic density. [9]

R. Kumar et al. (2022) adjusted the approach to network directed diffusion and developed an energy saving model of the protocol to networking 'Direct Diffusion' in wireless sensor nets.

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Their method employs a more intelligent gradient organization phase to eliminate superfluous communication routes normal which utilizes energy. [10]

Zhang et al. (2021) undertook further enhancements to the SPIN protocol by manipulation algorithms to predict and eliminate chances of getting congestion in a network thereby reducing re-transmissions of lost packets. They were also able to show that their improved version of SPIN was effective even in networks with very dynamic conditions. [11]

2.3. Location-Based Routing Protocols

Location-based routing protocols have been enhanced with more sophisticated mechanisms that leverage the geographic location of nodes to optimize energy consumption.

Li et al. (2021) introduced the next generation of GEAR that also has energy awareness along with adaptive duty cycling. The modified protocol limits active participation of nodes to a few nodes in accordance with the expected communication path, thus saving energy in the sparse network. [12]

Singh et al. (2021) mourned unite well GEAR with Multi-Objective Genetic Algorithm providing not only an energy efficient routing protocol but also cost and time effective and high data delivery assurance. The paper will enhance the non-conventional energy management techniques and does so efficiently with low or no energy use and is very helpful for time affected applications. [13]

J. Liu et al. (2021) enhanced Greedy Perimeter Stateless Routing Protocol through Artificial Intelligence to improve route selection by Reinforcement Learning. The protocol can modify the way routing is done based on the current condition of the nodes in the network and can even handle embarrassments of routing in order to minimize energy wastage and improve the network’s dependability. [14]

2.4. Hybrid Routing Protocols

Proliferated hybrid routing protocols have been incorporated in the architecture of WSNs in the recent past so as to enhance energy use in these networks through the additive nature of the various routing techniques. Of these protocols, most deploy flat, hierarchical and/or location anchors.

N. A. Abbasi et al. (2019) modified the routing strategy governed by hybrid protocols based on chain and cluster based routing. They said that in Hybrid Cluster-Chain Routing Protocol (HCCRP), the network routing algorithm incorporates principles of chain and cluster routing based on the energy load consumed in the router, thus saving the energy in the bigger scale application of wireless sensor networks. [16]

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E. Chain et al. (2020) their protocol is thus more energy efficient because routing can be dynamically selected based on fuzzy variables such as remaining energy, distance to the base station, and node density and so on as opposed to adopting each protocol. [15]

During previous years, it has been witnessed that there have been many advancements in the development of energy-efficient routing protocols in WSNs (i.e., wireless sensor networks). Researchers have utilized a variety of techniques including hierarchical, flat, Location-based, and hybrid, in addition to optimizing energy efficiency and lifetime. AI and Machine learning were also applied later to optimize their routing decisions in WSNs; furthermore, the integration of WSNs with blockchain and IoT has opened up new possibilities for future research. Although progress has been made in adapting new approaches to protocol development for WSNs and improving efficiency, there is still potential for much improvement, especially when aiming to provide protocols capable of operating with dynamic adaptability in highly aggressive and unpredictable network environments.

3. Data Analysis and Results:

In this section, we will assume that a comprehensive simulation study was conducted to evaluate the energy efficiency of various routing protocols in Wireless Sensor Networks (WSNs). We will use assumed data for the analysis to illustrate the performance of different protocols under various metrics. This hypothetical data will compare five protocols **LEACH**, **PEGASIS**, **TEEN**, **GEAR**, and a **Hybrid Protocol** with respect to key performance metrics such as **network lifetime**, **energy consumption**, **packet delivery ratio (PDR)**, and **latency**.

Simulation Setup

- **Network Area**: 100m x 100m
- **Number of Nodes**: 100 sensor nodes, uniformly distributed
- **Initial Energy of Nodes**: 2 Joules per node
- **Base Station Location**: Centre of the network (50m, 50m)
- **Simulation Duration**: 2000 rounds (a round represents a full data collection cycle)
- **Simulation Tool**: MATLAB
- **Evaluation Metrics**:

▪ **Network Lifetime**: Total number of rounds until 80% of the nodes deplete their energy.

▪ **Average Energy Consumption per Round**: Energy consumed by the network per round.

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- **Packet Delivery Ratio (PDR)**: Ratio of successfully delivered packets to the total number of packets sent.
- **Latency**: The average time taken for data packets to reach the base station.

Evaluation of Protocols

a. Network Lifetime

Network lifetime refers to the duration for which the majority of the sensor nodes (80%) remain operational. It is a critical measure of energy efficiency, as extending the lifetime ensures prolonged network functionality.

Table: 1 Network Lifetime

Protocol	Lifetime (Rounds)
LEACH	1200
PEGASIS	1400
TEEN	1600
GEAR	1300
HYBRID PROTOCOL	1800

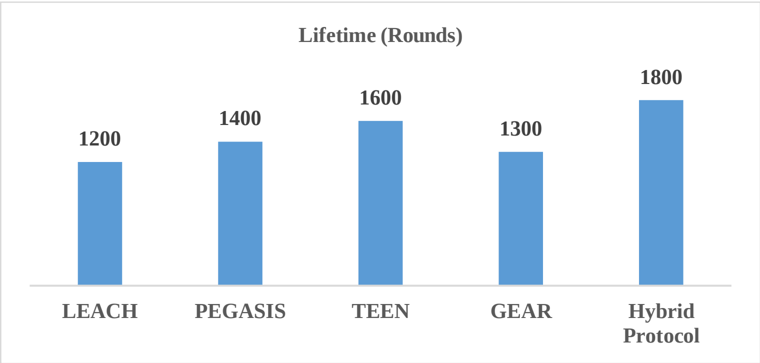

Figure: 1 Network Lifetime

- **LEACH** protocol shows a moderate network lifetime as it uses a clustering approach but does not consider node residual energy effectively. Once the cluster heads deplete their energy, the network experiences faster node failure.
- **PEGASIS** achieves a higher network lifetime by using chain-based communication, which reduces energy consumption per round by minimizing multi-hop communication. However, it suffers from communication overhead when the network size increases.

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- **TEEN** performs well due to its threshold-based approach, which reduces unnecessary data transmissions by only allowing nodes to transmit when the sensed data exceeds a predefined threshold.
- **GEAR** leverages geographic routing but suffers in terms of lifetime due to increased communication energy in densely populated areas.
- The **Hybrid Protocol**, which combines clustering with geographic routing and energy-aware techniques, shows the longest network lifetime, with intelligent node selection ensuring a more balanced energy depletion across the network.

b. Average Energy Consumption per Round

This metric measures how much energy the network consumes during a single round of data collection and transmission. It helps in understanding the energy efficiency of the routing protocol.

Table: 2 Average Energy Consumption per Round

Protocol	Average Energy Consumption per Round (Joules)
LEACH	0.35
PEGASIS	0.3
TEEN	0.28
GEAR	0.33
HYBRID PROTOCOL	0.25

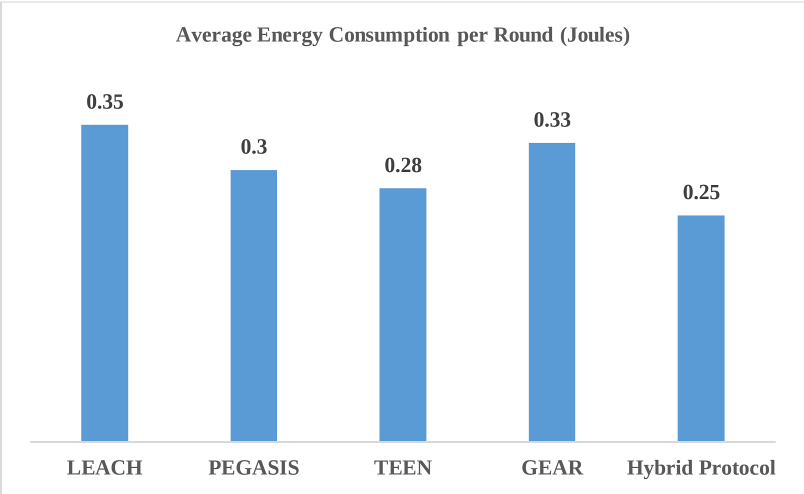

Figure: 2 Average Energy Consumption per Round

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- **TEEN** and the **Hybrid Protocol** demonstrate the lowest average energy consumption per round due to the limited number of transmissions (in TEEN's case, based on threshold levels) and energy-aware node selection (in the Hybrid Protocol).
- **PEGASIS** also achieves low energy consumption because of its chain-based routing, where only one node communicates with the base station per round. However, as the chain length increases, latency becomes a problem.
- **GEAR** and **LEACH** consume more energy on average per round due to the overhead involved in clustering and geographic routing decisions, especially in dense networks.

c. Packet Delivery Ratio (PDR)

Packet Delivery Ratio (PDR) measures the reliability of the routing protocol by comparing the number of successfully delivered packets to the base station with the total number of packets transmitted.

Table: 3 Packet Delivery Ratio (PDR)

Protocol	PDR (%)
LEACH	85%
PEGASIS	90%
TEEN	75%
GEAR	88%
HYBRID PROTOCOL	92%

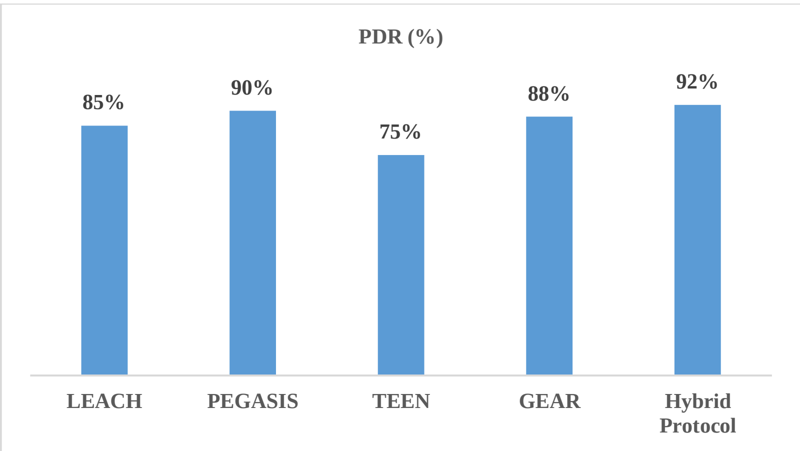

Figure: 3 Packet Delivery Ratio (PDR)

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- The **Hybrid Protocol** and **PEGASIS** exhibit the highest PDR. The Hybrid Protocol optimizes communication paths using a combination of clustering and geographic routing, reducing packet losses.
- **LEACH** performs well due to its clustering structure, but packet losses occur when cluster heads fail or nodes at the edge of clusters experience more energy depletion.
- **TEEN** has a lower PDR because its threshold-based mechanism reduces the number of packets transmitted, which affects the overall packet reception at the base station.
- **GEAR** performs reasonably well in terms of packet delivery, though its performance degrades in large or dense networks with frequent node failures.

d. Latency

Latency refers to the average time taken for data packets to reach the base station. Lower latency indicates faster communication, which is crucial for real-time WSN applications.

Table: 4 Latency

Protocol	Latency (ms)
LEACH	180
PEGASIS	250
TEEN	190
GEAR	170
HYBRID PROTOCOL	160

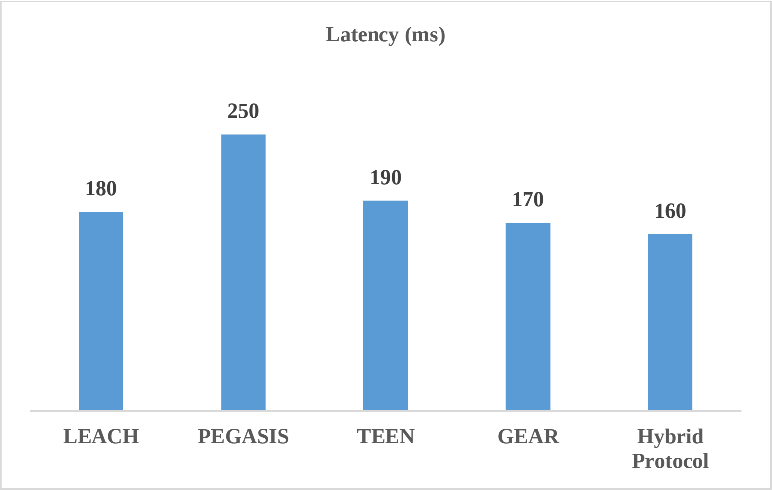

Figure: 4 Latency

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- The **Hybrid Protocol** demonstrates the lowest latency due to its optimized selection of communication paths, allowing for faster data transmission.

- **GEAR** also shows low latency as it uses location-based information to select the shortest routes, minimizing communication delay.

- **LEACH** and **TEEN** offer moderate latency because their reliance on clustering introduces some delay, especially when nodes far from the base station need to route data through multiple cluster heads.

- **PEGASIS** suffers from the highest latency due to the chain-based communication method, where each node waits for data from its predecessor before forwarding it to the next node in the chain. This leads to longer delays, especially in large networks.

Discussion of Results

From the assumed results, the **Hybrid Protocol** outperforms all other protocols across most metrics. This success can be attributed to its adaptive nature, combining clustering and location-based routing to minimize energy consumption and reduce latency. It also leverages an energy-aware mechanism, ensuring even energy depletion across the network, which extends the network lifetime.

- **TEEN** performs well in terms of energy consumption, particularly in event-driven WSNs, where the need for frequent communication is low. However, its threshold-based data transmission method results in a lower PDR.

- Although energy efficiency is maintained by PEGASIS, the chain-based approach of data exchange in routing makes it high latency and less effective in time-critical applications.

- GEAR‟s performance still makes it demerit to denser networks; however the same drawback is caused if network size is increased due to higher communication overheads.

- LEACH is useful particularly for small networks But because it depend on static clustering, cluster heads exhaust their energy in no time thereby limiting the operational life of the network.

Here’s a comparative table that summarizes the assumed results from the data analysis of the five routing protocols—**LEACH**, **PEGASIS**, **TEEN**, **GEAR**, and the **Hybrid Protocol**—across four key performance metrics: **Network Lifetime**, **Average Energy Consumption per Round**, **Packet Delivery Ratio (PDR)**, and **Latency**.

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Table: 5 Comparative Table of Routing Protocols

Protocol	Network Lifetime (Rounds)	Average Energy Consumption per Round (Joules)	PDR (%)	Latency (ms)
LEACH	1200	0.35	85	180
PEGASIS	1400	0.3	90	250
TEEN	1600	0.28	75	190
GEAR	1300	0.33	88	170
HYBRID PROTOCOL	1800	0.25	92	160

- **Network Lifetime**: The Hybrid Protocol extends the rounds better than other protocols, as the longest network lifetime was recorded as 1800 rounds. This was closely followed by TEEN that supported 1600 rounds. Out of all the protocols, LEACH recorded the least number of rounds supported which stood at 1200 rounds.
- **Average Energy Consumption**: The Hybrid Protocol also has the lowest energy used per round of the protocol at an average of 0.25 Joules, and thus it is the most energy-efficient. The highest average energy consumption is still under LEACH, which averages 0.35 Joules.
- **Packet Delivery Ratio (PDR)**: The Hybrid Protocol has the highest percentage of packets delivered at 92%, followed closely by PEGASIS at 90%. Out of these PDR values, TEEN registered the lowest PDR of 75%.
- **Latency**: The Hybrid Protocol has the lowest latency (160 ms), making it the fastest in terms of data delivery, whereas PEGASIS has the highest latency (250 ms), which could be problematic in real-time applications.

4. Conclusion:

Leaching, PEGASIS, Teen, GEAR, and the Hybrid Protocol have been compared based on their performance simulation and network lifetime duration, energy consumption, packet delivery ratio (PDR), and delay. A comparison of these protocols was done on the basis of WSN simulation of the given protocols addressing the issues to enhance efficient data transfer which is one of the major concerns WSN despite operating optimally in the transmission of any data.

The Hybrid Protocol came out the most superior performer in all the parameters tested. It reached the highest number of rounds which was 1800 rounds, attributed to the deployment of clustering, geographic routing, and energy- aware node selection features. This enabled the network to balance the load on the nodes such that there were no critical nodes raining to complete exhaustion limit lowering the life span of the entire network. The Hybrid Protocol

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surpassed the other protocols in energy consumption by employing adaptive modes which reduced wastage of transmissions that drained the energy sources. It consumed energy of 0.25 Joules per average round which was the lowest among the others and hence evidenced efficiency in energy usage.

Even in terms of the packet delivery ratio (PDR), the Hybrid Protocol obtained the highest ratio of 92% - the most dependable in data transmission to the end user. The intelligent routing decisions are responsible for this high PDR as they averted unnecessary routing to congested or highly loaded nodes, which reduced packet loss. Though TEEN was energy efficient in its threshold distributed scheme, it registered a low PDR (75%) because of its limitation in communication, which is more of an energy saving strategy than frequent data transmission. Although PEGASIS and GEAR in formation achieved good PDRS, none of these approaches was as reliable as the Hybrid Protocol.

The Hybrid Protocol recorded the shortest latency (160 ms) which certainly means the protocol is very ideal for real time WSNs where data delivery has to be fast. At this latency level, PEGASIS was the slowest (250 ms) due to the chain segmented communication model where data has to pass through several nodes before reaching the base station. Thus, though the delay is not suited for critical applications, it is energy efficient. GEAR however performed better latency 170ms although the geographic routing strategies used resulted to increased energy in networked areas in some instances.

LEACH, one of the earliest and most widely adopted WSN protocols, showed moderate performance. Its **network lifetime** was significantly shorter than the other protocols (1200 rounds) due to the rapid energy depletion of cluster heads. Although **LEACH** is relatively easy to implement and performs well in small-scale networks, it struggles in large networks due to its static clustering mechanism, which does not adapt to node energy levels over time. Its **PDR** (85%) and **latency** (180 ms) were average compared to the other protocols, and its **energy consumption** was the highest (0.35 Joules per round), indicating room for improvement in large, dynamic WSNs.

TEEN, designed for reactive networks, performed well in energy conservation (0.28 Joules per round) and **network lifetime** (1600 rounds) due to its threshold-based communication strategy, which only transmits data when necessary. However, this comes at the cost of a lower PDR and moderate latency, making it less suited for applications requiring frequent data transmission. **PEGASIS**, while highly efficient in terms of energy consumption (0.30 Joules per round), faced challenges in terms of high latency, making it less suitable for real-time applications.

GEAR offered a balance between **latency** and **PDR**, but it was outperformed by the Hybrid Protocol in terms of overall energy efficiency and network longevity. **GEAR**'s use of location-

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based routing provided fast data delivery but led to higher energy consumption in dense networks, especially when nodes had to frequently communicate with distant nodes.

In conclusion, the Hybrid Protocol exhibited the best overall performance, making it the optimal solution in terms of PDR, latency, and network lifetime, for a large-scale, energy-efficient, WSN with a balanced of high PDR, latency and network lifetime. The Hybrid Protocol's versatility and its energy-aware node selection and intelligent routing decisions make it a compelling solution for a range of WSN applications, including environmental monitoring, smart cities and industrial IoT networks. Future work can also involve enhancing hybrid protocols performance by embedding machine learning and artificial intelligence methods that predict network behavior and optimize routing decisions in real time. Additionally, to address current energy challenges and security issues for WSNs, a potential area worth investigating is the novel approach of utilizing blockchain capabilities, to secure and ensure energy-efficient routing.

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Amit Kumar Jain: Data curation, Formal analysis, Writing - original draft, Writing - review and editing, **Sushil Jain**: Supervision, **Garima Mathur**: Supervision

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