



Development of an Efficient Cluster-Based Hybrid LEACH+TEEN Protocol for Time-Critical WSN Application

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Abstract

Wireless Sensor Networks (WSNs) play a crucial role in monitoring and data collection for various real-time applications, including environmental surveillance, industrial automation, and smart cities. However, achieving energy efficiency and timely data delivery remains a critical challenge, especially in time-sensitive scenarios. This research presents the development of an efficient cluster-based hybrid routing protocol that combines the strengths of Low-Energy Adaptive Clustering Hierarchy (LEACH) and Threshold-sensitive Energy Efficient Network (TEEN) protocols to address these challenges. The proposed Hybrid LEACH-TEEN protocol dynamically adapts to both periodic and event-driven data transmission needs by integrating LEACH's randomized cluster-head selection and TEEN's threshold-based data transmission mechanism. This hybrid approach significantly reduces redundant transmissions and optimizes energy consumption across the network. Extensive simulations were conducted to evaluate the protocol's performance in terms of network lifetime, stability period, energy consumption, and the number of alive nodes over time. Results demonstrate that the Hybrid protocol outperforms traditional LEACH and TEEN protocols, particularly in time-critical applications, by ensuring prompt response to critical events while maintaining energy-efficient operation. This work contributes to the design of intelligent and adaptive routing strategies for next-generation WSNs.

Keywords: LEACH; TEEN; DDR; E-LEACH; M-LEACH; Hybrid Protocol

1. Introduction

Wireless sensor networks are one of the most important scientific technological innovations, as the applications of these networks have become very wide in industry, military, agricultural automation, healthcare, environmental monitoring, smart cities, and security monitoring. WSN demonstrate advantages through their inexpensive nature, exceptional reliability against failures and their power-efficient design together with multiple operational functions [1]. The network contains distributed sensor nodes that collect and process data while sending it to a central base station for evaluation [2,3,4]. Energy efficiency is the main obstacle for wireless sensor networks because battery-powered nodes operate in deployments that make battery replacement impossible. The necessary improvement in energy management in wireless sensor networks serves to increase the network uptime while maintaining data reliability [5]. The large-scale deployment of wireless sensor networks requires increasing the density of nodes by analyzing the propagation characteristics of the target domain. Wireless networks are subject to natural failures, especially the collapse of sensor nodes due to power failure and communication outage. The development of hardware

and software must include robustness features with continuous functionality to avoid the failure of system components when operating in difficult-to-access conditions. Therefore, multiple operational protocols have been established to enhance the network longevity and reduce energy consumption while achieving the routing strategies of nodes. These protocols differ based on their nature and purpose. Energy Efficient Routing Protocols (EERP) belong among these set of protocols [6]. The energy-saving protocol allows sensor nodes to enter sleep mode which results in extended battery life together with enhanced network duration. Clustering techniques referred to as (LEACH) represent some of these protocols [7,8]. The low-power adaptive clustering hierarchy divides a sensor area into clusters therefore decreases power utilization by carefully locating nodes and enabling communication between multiple-hop destinations, which enhances network lifetime performance. The Energy and Lifetime Enhancement of Node Optimization Protocol (ENELIP) [9] divides wireless sensor networks into balanced subnetworks through its size-based partitioning mechanism that enhances cluster-based energy optimization within network routes. HEERPOP uses reliability and traffic criteria for path selection, which enhances network performance by resolving packet loss and energy drainage problems [10]. These protocols reduce energy consumption effectively but the implementation process introduces several challenges because networks need adaptive behavior to achieve stability [11]. While Distributed Energy Efficient Clusters (DEEC) improve the latency across nodes by efficiently managing energy [12], another protocol is a Geolocation-based Directional Information Relay (GEDIR) [13] to make routing decisions, improve energy consumption, and reduce data transmission costs. Flat routing protocols manage all nodes at similar levels through non-hierarchical communication structures that establish direct connections between nodes [14]. Due to their simplicity, they may not achieve the same energy conservation as other routing protocols. Future research focuses on improving and integrating energy-efficient protocols and cybersecurity improvement methods to enhance the reliability of dynamic networks [15,16,17].

1.1 Problem Statement

In the medical, military, environmental, and manufacturing, WSNs serve as basic technological infrastructure to collect and monitor data in real-time. Sensor networks have limited power by which they can connect to the base station (BS) wirelessly [18,19].

Energy efficiency stands as the main obstacle in WSNs because sensor nodes work with non-rechargeable batteries, which causes power depletion problems that decrease network duration and affects operational capability. Different hierarchical routing protocols exist today yet Low-Energy Adaptive Clustering Hierarchy (LEACH) and Threshold-sensitive Energy Efficient Network (TEEN) stand as two primary examples used for addressing this problem. LEACH reduces energy usage through its mechanism of dynamic cluster head (CH) selection for data aggregation yet random CH pick ensures unbalanced energy consumption, which shortens network lifetime. TEEN implements threshold-based data transmission because nodes send data only if sensor readings surpass defined threshold levels thus minimizing communication waste. TEEN faces limitations when used continuously because its hard and soft threshold system can prevent important data transmission that causes information loss. A combined routing approach is needed to address the balance between energy consumption, data efficiency, and network durability. This research develops the hybrid LEACH-TEEN protocol, which combines adaptive clustering and threshold-based reporting to address the key performance issues of LEACH and TEEN, while improving energy efficiency and extending both lifespan and throughput while reducing end-to-end delay and communication overhead [20].

2. Related Work

Researchers investigated different enhancement methods to boost both energy efficiency and network longevity in TEEN. These developments use enhancements to the protocol's clustering and routing strategies because these elements are essential for decreasing energy usage while extending sensor network operational lifespan. This section outlines the fundamental improvements and technique applications used on TEEN alongside other related protocols. In 2023, the authors Kurda et. al., proposed an improvement to the enhanced LEACH protocol. The E-LEACH protocol uses clustering to reduce the amount of communication between sensors and the base station, and an energy analysis shows that the method saves 38.2% more energy than the M-LEACH protocol in its operation. The E-LEACH

algorithm achieves a network scalability of 69%, while the LEACH protocol reaches 59.2%, and the network lifetime without LEACH is 48% [21].

The authors Dongare. et. al. in 2024 developed aerem-LEACH which determines appropriate communication channel numbers and keeps distant receiver nodes out of cluster formation to minimize sensor node energy usage effectively. The researchers developed a new channel selection threshold for their energy-efficient network, which included free space as well as multi-hop communication and the hybrid model. The results showed that the energy consumption of the wireless sensor network (WSN) using the aerem-LEACH routing protocol was significantly reduced compared to traditional routing protocols [22].

The authors Mythili, et, al., in 2024 compared LEACH, HEED, and TEEN with the CoSwarm-LEACH protocol for energy-efficient routing through performance metrics testing, which showed that CoSwarm-LEACH achieved superior results than previous routing protocols in terms of latency, network overhead, energy consumption, and throughput [23].

The researchers KS. in 2020 presented a performance analysis and comparison of the proposed FL-NC-EE (Energy-Efficient Fuzzy Logic Network Coding) routing protocol. They analyzed the performance of LEACH and its variants, LEACH-FL, K-Means-LEACH, and FL-EE/D, using NS2. They demonstrated that FL-NC-EE achieved superior results compared to competing routing protocols in terms of energy efficiency and network lifetime [24].

The researchers Mechta in 2021 presented an ACOMAR protocol that outperforms LEMAR by offering 80% better latency, 20% better energy savings, 81% fewer hops, and a 54% higher throughput, making it a suitable solution for healthcare applications that require rapid interaction between WSN-based critical IoT devices in emergencies. [25].

Madhavan et., al., in 2025 developed CFS-BWO as a strategy to improve lowering energy usage and enhancing network operational duration. The team applied average delay together with residual energy and distance and communication cost to determine the best solution for channel and path selection. The performance evaluation used 0.87 J as the residual energy value [26].

Researchers Hebal et. al. in 2020 proposed a new approach for LEMAR-WSN routing, which combines information about communication parameters and accumulated energy levels to develop time division multiple access (TDMA) features and optimize power for wireless sensor networks. Simulations indicate that the newly proposed method improves communication latency by 20% and improves energy consumption on average [27].

The research conducted by Hamdy H., et. al. in 2024 introduces NN_ILEACH as a neural network-based routing protocol which increases Wireless Sensor Network energy efficiency and longevity while delivering better throughput and packet delivery ratio than LEACH and ILEACH systems at a 20-fold longer network lifespan [28].

Patil, et. al., in 2018 they proposed a novel approach for adding multiple applications to the TEEN protocol for wireless sensor networks and prioritization. ApriTEEN achieves similar network throughput levels to TEEN in both heterogeneous and homogeneous environments, while demonstrating better network stability (11%) and longer lifetime (9%). According to the research results, ApriTEEN performs better in heterogeneous environments, increasing network stability by 9% and increasing network lifetime by 12.4% [29].

S. Lindsey et. al. in 2022 proposed a near-optimal chain-based protocol, PEGASIS (Energy-Efficient Aggregation in Sensor Information Systems), which improves the LEACH protocol. In that paper, simulation results showed that PEGASIS performs 100% to 300% better than LEACH when 1%, 20%, 50%, and 100% of nodes are down due to varying network capacities and topologies [30].

3. Methodology

Figure 1 demonstrates the overall idea of the research methodology. The network is started with initial set up in which randomly deploy the NN sensor nodes in an enclosed area as well as assign initial power to all nodes, designate location of the base station (BS) and details the LEACH and TEEN protocols.

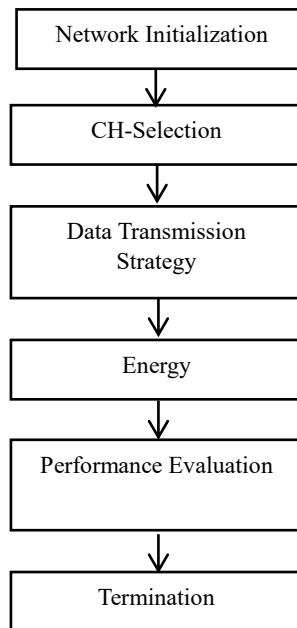


Figure 1. General framework of LEACH-TEEN

Selection of cluster heads (CHs) occurs according to LEACH algorithm and considers the remaining power and data transmission follows the adaptive threshold strategy (HT and ST) applied in TEEN.

Energy management include scheduling of sleep, adaptive cluster head rotation, multi-hop routing, and dynamic thresholding on the condition of the network. The assessment metrics of network performance are network lifetime, number of transmitted packets, and energy efficiency and the simulation stops when all nodes deplete energy.

The current paper introduces a combined protocol whose features act independently to solve the main problems with performance of LEACH and TEEN adaptive clustering and threshold-based reporting, introduced in a hybrid protocol LEACH-TEEN. In case of the use of LEACH in CH selection, the data transfer and adaptive threshold apply (TEEN). Below is a detailed explanation of all the steps mentioned in Figure 1.

3.1. Network Initialization:

Includes the following:

- a. Deploy N sensor nodes randomly in a (X × Y) area.
- b. Assign initial energy E₀ to each node.
- c. Define base station (BS) location and transmission range.
- d. Set the LEACH parameters: probability of p-group formation, threshold energy Eth, while the TEEN parameters are hard threshold (HT) and soft threshold (ST).

3.2. CH – Selection: cluster head is determined according to LEACH-Based as following:

- a. Compute CH probability for each node using as shown in equation 1:

$$P(n) = \frac{p}{1-p \times (r \bmod 1/p)} \dots\dots\dots (1)$$

Where:

- p is a fixed value (which may possibly be a probability between 0 and 1),
 - $r \bmod 1/p$, is the modulo operation of a value r with respect to $1/p$,
 - $P(n)$ is defined as a function of n , though n is not explicitly used in the formula (possibly implied via r).
- b. Select nodes with highest residual energy as CHs.
 - c. CHs broadcast advertisements to member nodes.
 - d. Non-CH nodes join the nearest CH based on signal strength.

3.3. Data Transmission Strategy:

Data transmission is implemented through adaptive thresholding (i.e. TEEN-Based) as the following steps:

- a. CHs assign Hard Threshold (HT) (minimum event detection value) and Soft Threshold (ST) (smallest change that triggers transmission).
- b. If sensor reading \geq HT, node transmits data to CH.
- c. If reading changes by \geq ST, node retransmits updated data.
- d. CHs aggregate received data to reduce redundant transmissions.
- e. CHs transmit compressed data to the BS.

3.4. Energy Management:

The following steps explain the optimization mechanisms of energy management:

- a. Sleep Scheduling: Nodes in idle state enter sleep mode to save energy.
- b. Adaptive CH Rotation: Rotate CHs dynamically based on residual energy.
- c. Multi-hop Transmission: CHs use multi-hop routing to the BS to avoid direct transmissions.
- d. Threshold Adjustment: Dynamically adjust HT and ST based on network conditions.

3.5. Performance Evaluation:

The final part of the proposed protocol is assessing the work through evaluated the performance metrics such as:

- a. Network Lifetime (Rounds): Measure rounds until first/last node dies.
- b. Alive Nodes: Monitor number of active nodes per round.
- c. Packet Transmission: Track successfully delivered packets.
- d. Energy Efficiency: Compute average residual energy per node.

3.6. Termination: the following conditions is considered for termination:

- a. Repeat steps 2–5 until all nodes deplete energy.
- b. Stop execution and analyze performance results.

4. Experiments and Results

A. Network Approach

The following assumptions are considered in this model: the location of the base station at the edge of the field (100, 50), all sensors have the same power, computation, and communication range. Overall nodes are distributed randomly in 100 m² area. The simulation is carried out with setting parameters table (1).

Table 1: Simulation parameters

Parameter	Value
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Network Area	100 × 100 m ²
Number of sensor nodes (N)	100
Initial Energy per Node (E _o)	0.5 J
Send and Receive Energy (E _{sr})	50nJ/bit
Transmit Amplifier Energy (E _a)	100 pJ/bit/m ²
Data Message Size (L)	2000 bits
Control Message Size (L _{ctrl})	100 bits
Data Aggregation Energy (E _{DA})	5 nJ/bit/signal
Free Space Model (E _{fs})	10 pJ/bit/m ²
Multipath Model (E _{mp})	0.0013 pJ/bit/m ⁴
Threshold Distance (d ₀)	Calculated from $\sqrt{(E_{fs} / E_{mp})}$
Cluster Head Probability (p)	0.05
Hard Threshold (HT)	100 (for TEEN component)
Soft Threshold (ST)	2
Transmission Range	20 meters
Duty Cycle Sleep Factor	0.1
Energy Threshold	0.1 J

B. Energy Consumed

The total consumed energy model per round can be split as shown in equation 2

$$E_{total} = E_{CH} + E_{nonCH} + E_{BS} + E_{control} \dots\dots\dots (2)$$

Where:

- E_{CH}: Energy consumed by Cluster Heads
- E_{nonCH}: Energy consumed by non-CH nodes
- E_{CHtoBS}: Energy for transmitting from CH to Base Station
- E_{control}: Energy for transmitting control packets (ADV, Join-REQ)

$$E_{CH} = N_{CH} \cdot (E_{DA} \cdot n + E_{sr} \cdot L + E_{mp} \cdot L \cdot d_{BS}^4)$$

Where:

- N_{CH}: Number of cluster heads
- n: Number of member nodes per cluster
- L: Data packet size (bits)
- D_{BS}: Distance from CH to BS
- E_{DA}: Data aggregation energy
- E_{sr}: Consumed energy per bit during sending or receiving
- E_{mp}: Amplifier energy (multipath)

The energy consumed by nodes not in cluster heads (non-CH) is represented in Equation 3.

$$E_{nonCH} = (N - N_{CH}) \cdot (E_{sr} \cdot L + E_{fs} \cdot L \cdot d_{CH}^2) \dots\dots\dots (3)$$

Where:

- d_{CH}: Distance from node to its CH
- E_{fs}: Free-space model amplifier energy

The amount of the energy required by the entire network of nodes to deliver control messages as shown equation 4

$$E_{\text{control}} = N \cdot (E_{\text{sr}} \cdot L_{\text{ctrl}}) \dots \dots \dots (4)$$

Where:

- L_{ctrl} : Control packet size (e.g., ADV, Join-REQ)
- Improved cluster head selection based on: residual energy, distance to base station and node density factor.
 Enhanced Data Transmission Strategy for the proposed hybrid protocol:
- TEEN’s threshold-based data reporting combined with LEACH’s periodic clustering.
 - Sleep scheduling based on a duty cycle factor.

C. Performance Metrics

To evaluate the system's performance, the following metrics were taken into consideration:

- **Energy Consumption:** Total energy consumed per round.
- **Network Lifetime:** Number of rounds until first/last node dies.
- **Throughput:** Total packets received at the base station.
- **Data Delivery Ratio (DDR):** Packets received/packets sent.
- **End-to-End Delay:** Average delay in data transmission.
- **Hops Per Round:** Average number of hops to reach the base station.

Here is a comparative overview of performance metrics for a Hybrid LEACH-TEEN protocol, compared to LEACH and TEEN, based on typical simulations and research studies in Wireless Sensor Networks (WSNs). This data assumes a standard WSN environment with homogeneous nodes and static base station, and is reflective of common results found in the literature.

Figure 2 shows the performance metric plot of the hybrid LEACH-TEEN protocol compared to the LEACH and TEEN protocols in terms of average remaining energy per round.

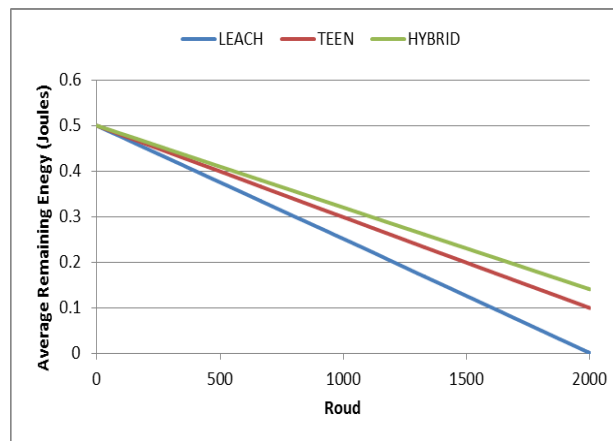


Figure 2. Average remaining energy vs. round.

From above we see that a hybrid saves more energy than LEACH and performs better than TEEN overall. Figure 3 reflects the comparative among LEACH-TEAN, LEACH and TEEN in term of alive node over 2000 rounds. As shown, the hybrid protocol sustains more live nodes over time, indicating a longer network lifetime.

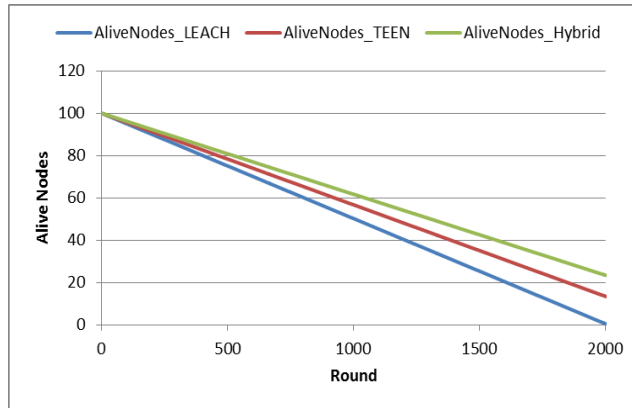


Figure 3. Alive nodes vs, rounds.

In term of Throughput, the Hybrid has higher throughput than the other protocols; indicates the successful data delivery rate over the network, as shown in figure 4 below.

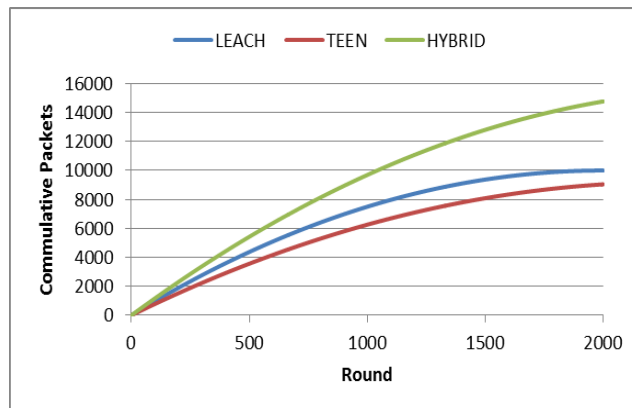


Figure 4. Throughput vs, rounds.

Figure 5, shows that the Hybrid protocol consistently maintains the highest data delivery ratio (DDR) than LEACH and TEEN protocols due to reduced congestion and redundant transmissions. This indicates that the hybrid protocol is a reliable network with minimal packet loss.

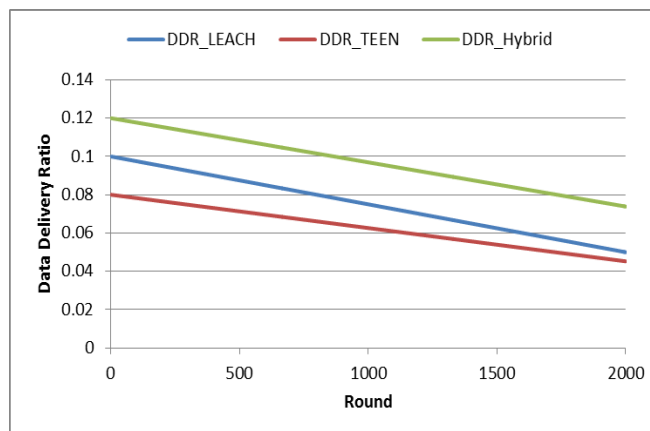


Figure 5. Data delivery ratio vs. round.

Figure 6 depicts average time taken for data to travel from a sensor node to the BS. As we see that the HYBRID achieves lower delay (0.35 sec.) for urgent data due to TEEN's threshold-triggered transmission than TEEN (0.4 se.) and LEACH (0.5 sec.).

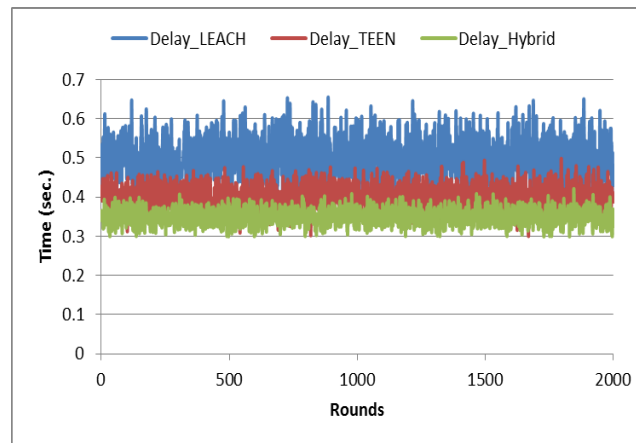


Figure 6. End-to-End Delay vs. round.

Finally, figure 8 shows that the Hybrid maintains balanced and lower hops due to efficient clustering, optimizing routing paths in term of the average hops per round.

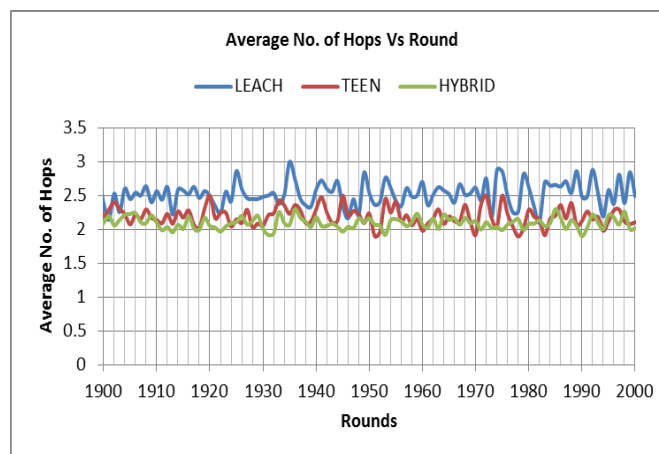


Figure 7. Average No. of Hops per Round.

5. Conclusion

In this work, the hybrid LEACH-TEEN protocol is presented as a performance improvement for wireless sensor networks. Where cluster head (CH) Selection is LEACH-Based and data transmission and adaptive thresholding is TEEN-Based. The simulation results showed the efficiency of the hybrid protocol compared to LEACH and TEEN protocols. That's where we found: The hybrid protocol inherits TEEN's threshold-based transmission control, which avoids unnecessary transmissions, and combines it with LEACH's periodic CH rotation for balanced load, Longer lifetime due to fewer transmissions (like TEEN) and better CH management (like LEACH), the throughput is higher than TEEN (which sends only when thresholds are crossed) and LEACH. Optimized for critical data delivery rather than constant flooding, in term of DDR & delay the hybrid approach optimizes when and what to send, reducing congestion and packet loss, while maintaining timely delivery, and the Hybrid maintains balanced and lower hops due to efficient clustering, optimizing routing paths in term of the average hops per round. This makes it well-suited for

time-critical WSN applications where energy efficiency and quick data delivery are essential. Future work may focus on integrating mobility support, fault tolerance, and AI-based adaptation for further improvement.

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