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A Review of Hierarchical Routing Protocols in Wireless Sensor Networks: Types and Recent Developments

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ABSTRACT

Wireless Sensor Networks (WSNs) are crucial in applications such as environmental monitoring, healthcare, and smart cities. However, the constrained energy resource of sensor nodes and the application may face some critical issues when a large number of sensor nodes are deployed with efficient data transmission. Previously, wireless sensor networks relied on flat routing protocols and location-based protocols for data transmission. Still, the main problem with flat routing protocols is that they perform inefficiently on a large network size. The results from direct communications amongst all nodes result in high energy consumption and congestion. These problems led to the development of hierarchical routing protocols (HRPs) to address these issues by organizing nodes into clusters, thus reducing energy consumption and improving network scalability. This reduces the communication overhead and extends the network's lifetime. This review paper reviews the challenges that led to the development of HRPs and recent developments that have been made for HRPs, with a focus on Power-Efficient GAthering in Sensor Information Systems (PEGASIS). It estimates the solutions these protocols offer and examines the remaining challenges, such as dynamic cluster management and load balancing. As a result, PEGASIS greatly improves energy efficiency and scalability, but there are still gaps for potential optimizations. So research efforts will be required in these areas to maximize performance and applicability for hierarchical routing protocols in WSNs

Keywords:
Wireless Sensor Networks (WSNs); Hierarchical Routing Protocols (HRPs); Energy Efficiency; LEACH; PEGASIS; Cluster-Based Routing

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1. INTRODUCTION

Wireless sensor networks (WSNs) are collections of compact-size, relatively inexpensive computational nodes that measure local environmental conditions or other parameters and forward such information to a central point for appropriate processing. WSN nodes can sense the environment, communicate with neighbouring nodes, and, in many cases, perform basic computations on the data being collected [1].

WSNs can always be found in applications like surveillance systems, human health monitoring, military operations, and environmental monitoring. WSNs have also been used in smart buildings and agriculture. It opens opportunities to connect the digital and real worlds with the power of WSNs [2]. Hierarchical routing protocols still have limitations and challenges that need to be addressed, such as energy efficiency, especially for high-density sensor networks. Hierarchical routing is considered essential in WSNs because it addresses the limitations posed by finite energy resources and the need to extend network lifespan.

Hierarchical structures, such as clustering, can significantly improve scalability, manage energy distribution more effectively, and reduce the energy-intensive tasks that would otherwise rapidly drain node power. Hierarchical protocols balance the network load by organising nodes into clusters or chains, which optimizes data aggregation and minimizes long-distance transmissions, ultimately enhancing the network's longevity [3].

Energy consumption and the lifetime of the whole WSN are the most fundamental constraints and are commonly used to evaluate the merit of WSN network protocols and algorithms. Designing reliable WSN systems in terms of security, energy efficiency, and adaptability is a challenge. Some of the performance indicators that have been used in analyzing different routing algorithms include node failure and data loss. The energy burden that different routing algorithms have and their limitations need to be given attention. Some factors that need balancing in designing WSN protocols are fault tolerance, energy efficiency, scalability, latency, power consumption, and network topology. [4].

As stated above, access to the location where sensor nodes are deployed is difficult. Hence, maximizing the lifespan of such nodes is essential for an effective monitoring system. These nodes are battery-driven, which has a lifespan. The energy of the whole network must, therefore, be stretched while ensuring adequate and fair distribution of the total energy to prevent a situation of energy depletion of the sensor node ahead of schedule. In the last few years, several routing protocols have been proposed and classified into different categories based on several parameters. Looking at it from a broad perspective, it emphasizes the need for energy consumption optimization in sensor networks [5].

Low Energy Adaptive Clustering Hierarchy (LEACH) is a classical and essential cluster-based protocol proposed to minimize energy consumption by efficiently selecting cluster heads. Forming small clusters within the network helps overcome these crucial issues through efficient resource utilization. For each cluster, a cluster head (CH) is elected to act as a hop between the sensing nodes and the sink, thereby reducing the transmission distance. The CHs are selected dynamically at some intervals to reduce the overhead [6].

This paper aims to provide an in-depth overview of hierarchical routing protocols in WSNs, both reviewing classic protocols and discussing recent advancements that enhance the dynamic requirements of WSN applications. Specifically, this review categorizes hierarchical protocols and discovers recent improvements that address common pitfalls in clustering and CH selection. The objective means evaluating which of the hierarchical routing protocols best solves the problems under those diverse conditions and identifies potential avenues for further research that could evolve more flexible and efficient routing solutions.

This review addresses the following research questions: (1) What are the strengths and limitations of classic hierarchical routing protocols in terms of energy efficiency, scalability, and data reliability? (2) How do recent advancements enhance the performance of hierarchical routing protocols, and what specific improvements do they bring? (3) Which hierarchical routing protocols are most suitable, and what areas need further exploration to address existing limitations?

The paper is organized as follows: Section 2 provides an overview of hierarchical routing fundamentals; Section 3 shows the major routing protocols in WSN; Section 4 reviews major protocols and recent developments; Section 5 discusses challenges and research gaps, and Section 6 concludes with final remarks and future directions.

2. BACKGROUND AND FUNDAMENTALS

WSNs are composed of a set of small, autonomous sensor nodes; as shown in Figure 1, these sensor nodes are deployed randomly or by robots in various environments to monitor physical or environmental conditions. These nodes are equipped with sensing, processing, and communication capabilities, allowing them to gather data, process it locally, and communicate wirelessly with a central hub or other nodes within the network [7] [8].

The architecture of WSNs typically includes sensor nodes and gateway or base station (BS) devices that can communicate with each other using radio channels and communication models. Sensor nodes are responsible for data collection and initial processing, while base stations act as gateways for data aggregation and transmission to external networks [7] [9].

The aggregated data will be processed and sent to the computers of staff in the office or at home through mobile devices or the Internet. From this information, users can make decisions in real time to solve the problem that occurred [10]. Communication within WSNs is often facilitated through wireless protocols, such as ZigBee, which is particularly favoured in scenarios where energy efficiency is crucial, as sensor nodes are typically battery-powered and have limited resources [11].

Sensor networks are made up of SNs, which can exist in small or large numbers. These nodes vary in size, and the SNs perform well in different domains based on the size of the nodes. Due to their unique architecture, SNs in WSNs often consist of a microcontroller that manages the monitoring, a transceiver that produces radio waves, and several kinds of wireless communication devices, in addition to an energy source like a battery. With sensors ranging in size, the entire network operates concurrently [12].

Through the use of a routing mechanism, their main goal is to provide the source data to the receiving node. Figure 2 shows the basic design of the Wireless Sensor Node unit.

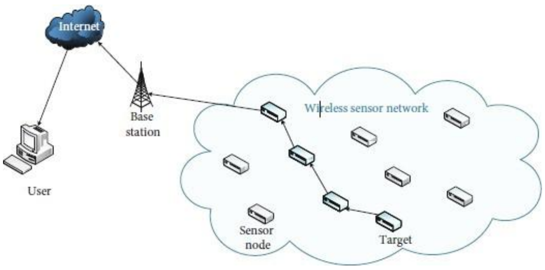

Fig. 1 Architecture of WSN

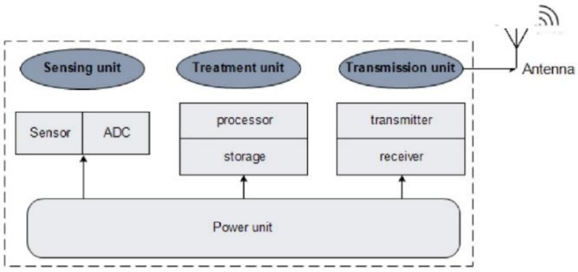

Fig. 2 Wireless Sensor Node Unit

WSNs have a wide range of applications across various fields. In disaster monitoring, they can be deployed to detect and report environmental changes, providing critical data for early warning systems [13]. Also used in measuring physical conditions and integrating with IoT and smart cities for energy-efficient, reliable, and cost-effective monitoring and control, Figure 3 shows the major fields in which WSN can be applied. These applications demonstrate the versatility and importance of WSNs in modern technology and their potential to become integral to various aspects of daily life.

2.1. Challenges in WSNs

The most important challenges are real-time transmission without delay, power management with good energy utilization, more secure and private protocols, high quality of service, scalability, heterogeneity, complexity, and better self-management [14]. Fault tolerance in WSNs is crucial for maintaining functionality, and redundancy-based methods like node and path redundancy enhance fault resilience, improving network reliability and data transmission accuracy [15]. As WSNs grow in size, efficient communication becomes increasingly challenging. Scalability issues can lead to delays and data loss, necessitating advanced algorithms that ensure reliable data transmission across numerous nodes [16].

WSNs face numerous challenges, with energy consumption being the most critical issue affecting network lifespan [17]. Sensor nodes are typically powered by batteries, and their batteries are limited and have a finite lifespan [16]. Also, the mobility of nodes and changing network conditions can increase energy consumption due to frequent re-routing and communication overhead [18].

In some applications, battery life is limited, and battery replacement or recharge is not possible, so effective energy management is required. Due to hostile deployment and uncontrolled conditions, high data transmission in WSN results in energy consumption, hot spot issues, packet loss, and sensor node breakdown [19]. While energy constraints are a primary concern, some researchers argue that focusing solely on energy efficiency may overlook other critical aspects, such as security and data integrity, which are equally vital for the successful deployment of WSNs [20].

2.2. Routing in WSN

Routing is critical in WSN because if a sensor node fails during data transmission, the wireless link becomes uncertain, and routing protocols must meet the SN’s power demands [21] [22]. Routing faces challenges due to limited energy resources, unreliable communication, and scalability issues [23]. Various routing protocols have been developed, categorized as data-centric, network structure, hierarchical, and location-based. Some classifications expand this to include mobility-based, multipath-based, heterogeneity-based, and QoS-based protocols [24].

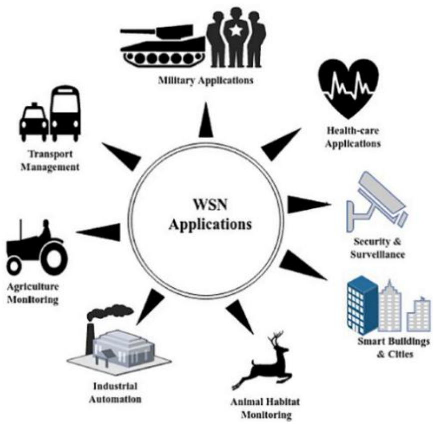

Fig. 3 Applications of WSN

Routing in WSNs aims to maximize network lifespan and energy efficiency while ensuring data delivery. Key design considerations include shortest paths, minimum energy consumption, reduced delay, and network longevity [25]. Energy-efficient routing strategies are crucial for WSNs due to the limited battery life of sensor nodes [26]. Clustering techniques are widely used in WSNs to improve energy efficiency, scalability, and network management [27] [28].

These techniques involve partitioning nodes into clusters with designated cluster heads (CHs) that communicate with the base station [29]. In general, the primary goal of routing in WSNs is to optimize energy consumption and extend the lifetime of the network while maintaining effective data transmission and security. Ongoing researchers focus on addressing these challenges and developing more efficient routing protocols for specific applications.

3. CLASSIFICATION OF HIERARCHICAL ROUTING PROTOCOLS

In a wireless sensor network, self-organizing algorithms and protocols are used. Routing techniques are necessary for data transfer and node-to-node communication. Routing strategies for WSNs have been proposed in many ways. Figure 4 illustrates the wide variety of routing protocol kinds [5].

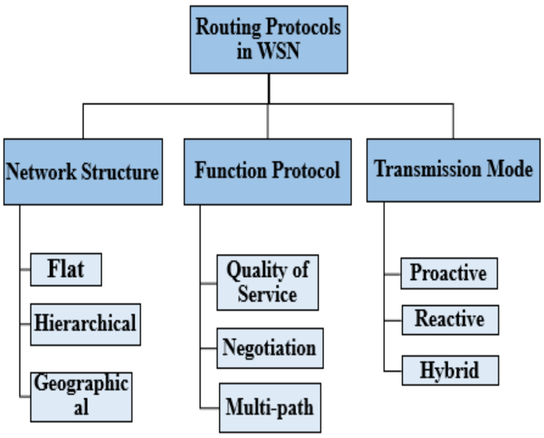

Fig. 4 Classification of Routing Protocols in WSN

WSNs employ various routing protocols to efficiently manage communication and energy consumption. These protocols can be broadly classified into three primary types: flat (data-centric), location-based, and hierarchical (cluster-based) [30]. Figure 5 shows the classification and types of wireless sensor network routing protocols, which show three types of routing protocols based on the network structure with some examples of each type.

3.1. Flat-based routing protocols

In flat-based networks, each node typically plays the same role, and sensor nodes collaborate to perform the sensing task. Also named multi-hop flat routing.

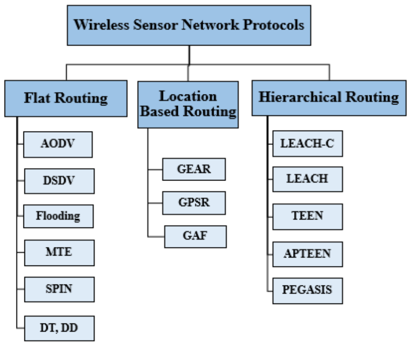

Fig. 5 Types of Network Structure Routing Protocols

The flooding technique is used by some flat-based routing, like SPIN, MCFA, directed diffusion, rumour routing, gradient-based routing, and energy-aware routing, which means that a node sends the received data or the management packet to its neighbours by broadcasting [31].

3.2. Hierarchical routing protocols

Hierarchical protocols, particularly clustering-based approaches, have gained prominence due to their ability to reduce redundant data transmission and balance the load among sensor nodes [32]. These protocols group nodes into clusters with elected cluster heads, which collect and aggregate data before sending them to the base station [33]. Recent research has focused on developing intelligent-based hierarchical routing protocols to optimize energy efficiency and network performance [34].

3.3. Location-based routing protocols

These protocols improve road safety and traffic control by facilitating efficient communication between infrastructure and vehicles in VANETs [35]. Location-based routing techniques have the ability to solve issues such as increasing propagation delay and node mobility. These protocols, such as GEAR and GAF, are designed to improve energy efficiency and quality of service for applications of the Internet of Underwater Things (IoUT) [36]. The problems of mobility, energy efficiency, and reliable data transfer in various network scenarios are solved by these protocols.

4. RECENT DEVELOPMENTS IN HIERARCHICAL ROUTING

The purpose of routing in a WSN is to keep the sensors operational as long as possible, increasing the useful life of the network. The routing methods are designed to use as little energy as possible for data transfer, allowing the network to remain active for longer periods [37].

Due to network topology, WSN routing protocols can be divided into three categories: flat, hierarchical, and location-based routing. Cluster-based routing improves scalability, increases network longevity, and improves energy efficiency by utilizing hierarchical structures for data aggregation. This method effectively distributes energy consumption among nodes, addressing energy challenges in WSNs while optimizing routing processes [38].

Energy-efficient routing protocols are designed to be a powerful mechanism for conserving energy in WSNs. Furthermore, among all types of routing protocols, hierarchical routing protocols are thought to provide the maximum energy efficiency [39]. Figure 6 illustrates hierarchical routing protocols in WSN.

4.1. Essential Hierarchical Routing Protocols

Network protocols must be designed to achieve fault tolerance in the presence of individual node failure while minimizing energy consumption [40].

Low Energy Adaptive Clustering Hierarchy (LEACH) is the pioneering protocol. It was proposed in 2000, and then other protocols, such as Power-Efficient GAthering in Sensor Information Systems (PEGASIS), improved upon LEACH by forming chains instead of clusters. Also, Threshold-sensitive Energy Efficient Networks (TEEN), Adaptive Periodic Threshold-sensitive Energy Efficient Networks (APTEEN), and Stable Election Protocol (SEP) improved over the LEACH protocol.

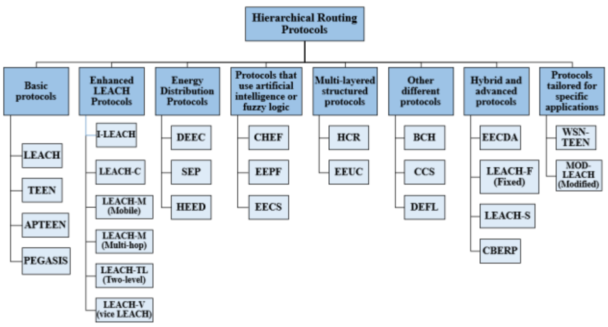

Fig. 6 Classification of Hierarchical Routing Protocols in WSN

In hierarchical routing, nodes are split according to energy levels, and each node is given a distinct role. The upper-level nodes are responsible for gathering and relaying the data to the base station(BS), whereas the lower-level nodes are responsible for sensing [41].

4.1.1. LEACH (Low Energy Adaptive Clustering Hierarchy)

In 2000, researchers developed the Low Energy Adaptive Clustering Hierarchy (LEACH), a clustering-based protocol that minimizes energy dissipation in sensor networks. The key features of LEACH are the localized coordination and control for cluster set-up and operation, randomized rotation of the cluster “base stations” or "cluster heads" as seen in Figure 7, and the corresponding clusters and local compression to reduce global communication [40].

As shown in Table 3, LEACH reduces energy consumption through dynamic cluster head rotation, but it suffers from uneven energy distribution in large-scale networks. When the network is divided into several sets of nodes or clusters, the hierarchical cluster architecture makes it easier for effective data aggregation and collection to occur independently of the expansion of wireless sensor networks and, in general, uses less energy and communications overall. Every cluster has a cluster head (CH) that manages the operations of the cluster’s other nodes (cluster nodes) [42] [27].

Researchers showed that LEACH uses much less energy than older methods and helps the network last longer. It is simple, works well, and has helped other researchers build better energy-saving methods for WSNs [40].

1.

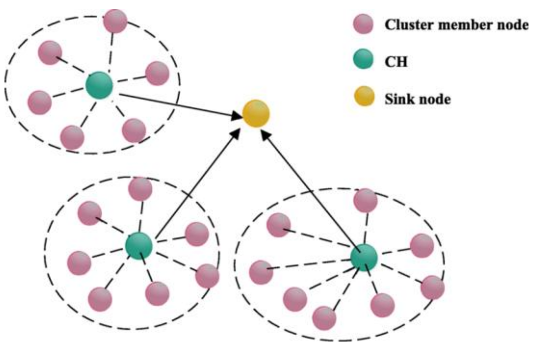

Fig. 7 LEACH Protocols in WSN

4.1.2. TEEN (Threshold-sensitive Energy Efficient Network Protocol)

TEEN (Threshold-sensitive Energy Efficient Network Protocol) was proposed in 2001 [43]; this protocol is an important method for reactive WSNs, created to work well in time-sensitive situations. It uses a special system based on thresholds, where the cluster head shares two main settings: the Hard Threshold (HT) and the Soft Threshold (ST). Figure 8 shows its structure.

The hard threshold is an absolute value of a sensed attribute, and nodes only transmit data when this value is exceeded. This ensures that only data relevant to the user is transmitted. The system uses a soft threshold to transmit only user-interested data, triggering transmission only if the difference from the last reported value meets or exceeds this threshold. This reduces unnecessary transmissions, optimizing energy usage [43]. As shown in Table 3, this protocol is efficient for time-sensitive applications and reduces unnecessary transmissions using hard and soft thresholds, but the data may be lost if thresholds are not met, and it is complex to manage due to dual thresholds.

4.1.3. APTEEN (Adaptive Periodic Threshold-Sensitive Energy Efficient Network)

APTEEN (Adaptive Periodic Threshold-sensitive Energy Efficient Network) was proposed in 2002. Its structure is the same as TEEN, as shown in Figure 8, and combines both planned data collection and quick responses to important events, offering flexibility for different types of applications. The protocol lets users set how often data is sent and when it should be transmitted, helping to control energy consumption while ensuring data accuracy. By changing the time intervals and threshold values, APTEEN optimizes energy usage, which is important for extending the network's lifespan. It also supports various types of queries, allowing users to request historical data, one-time updates, or continuous information from the network [44].

Since the protocol depends on thresholds, if these are not met, nodes may not send data, leading to missing information. The combination of regular and event-driven data transmission can make network management more complex and may increase delays.

4.1.4. PEGASIS (Power-Efficient GAthering in Sensor Information Systems)

The PEGASIS (Power-Efficient GAthering in Sensor Information Systems) protocol was proposed in 2002, which is an improvement over the LEACH protocol, but it enhances energy efficiency in sensor networks by using a chain communication system based on a greedy approach as shown in Figure 9, nodes send data to nearby nodes, where each node communicates only with its nearest neighbour.

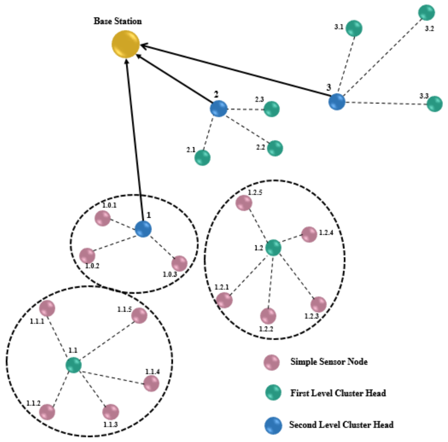

Fig. 8 TEEN and APTEEN Protocols

The leader, responsible for aggregating data and transmitting it to the base station, is selected in a round-robin manner.

The leader for round i is determined as:

$$\text{Leader}_{\,i} = \text{Node}_{\,(i \bmod N)} \quad (1)$$

Where:

- $\text{Leader}_{\,i}$ is the Leader for round i.
- N is the total number of nodes.
- i is the current round number.

Where *mod* is the division remainder of the current round (i) over the total number of nodes (N), if the number of rounds (i) is greater than the number of nodes (N), then the leader selection will be repeated.

This approach ensures that energy consumption is evenly distributed across the network. The total energy consumption for a node can be modeled as:

$$E_{total} = E_{tx} + E_{rx} + E_{agg} \quad (2)$$

Here, E_{tx}, E_{rx}, and E_{agg} represent the energy required for transmission, reception, and data aggregation, respectively. While PEGASIS significantly reduces energy consumption, it introduces delays due to the chain-based communication structure.

Each node, except the ones at the ends, combines data before sending it; only one node sends information to the main station during each round. However, forming clusters dynamically can be costly. Sending data over long distances to the main station uses a lot of energy. Also, the limited battery life of the nodes affects how long the network can last [45].

In addition, Table 1, which is shown in this section, provides the performance evaluation of hierarchical routing protocols. It reveals that PEGASIS outperforms other protocols in terms of network lifetime, with a maximum of 2000 rounds before the last node dies (LND). However, it also shows higher residual energy consumption than protocols like TEEN and APTEEN.

The table has been constructed based on previous research, which evaluated the performance of the protocols shown in Table 1, with initial energy equal to 0.5J and a 100x100 monitoring field with 100 nodes. The simulation parameters which were used are shown in detail in Table 1.

Table 1: The simulation parameters used in related works for performance evaluation.

Parameter	Value
Environment size	100x100 m^2
No. of nodes	100 nodes
Initial energy for normal node (E0)	0.5 J
Eelec	50 nJ/bit
Efs	10 pJ/bit/m2
Emp	0.0013 pJ/bit/m4
EDA	5 nJ/bit

As shown in Table 2, this protocol uses chain form to reduce energy consumption and extend network lifetime by minimizing long-distance transmissions, but it suffers from high delay in data transmission through chains and uneven energy consumption for nodes at the end of the chain.

Table 2: Performance evaluations and comparisons of essential hierarchical routing protocols.

Protocol	Network Lifetime (Rounds)			Residual Energy (J) in round = 500	Energy Efficiency (%)
	FND	HND	LND		
LEACH [64].	110	490	600	25	(15/25) =0.6%
TEEN [44].	500	1100	2150	24	0.625%
APTEEN [44].	500	850	1120	20	0.75%
PEGASIS [65].	1431	1608	2000	15	1%
SEP [64].	850	1020	1900	23.7	0.632%
HEED [66].	207	947	2384	23.5	0.638%

4.1.5. SEP (Stable Election Protocol)

SEP (Stable Election Protocol) was made in 2004 to handle the different energy levels of nodes in a wireless sensor network. It chooses cluster heads based on their starting energy, giving higher chances to nodes with more energy. This helps the network by last

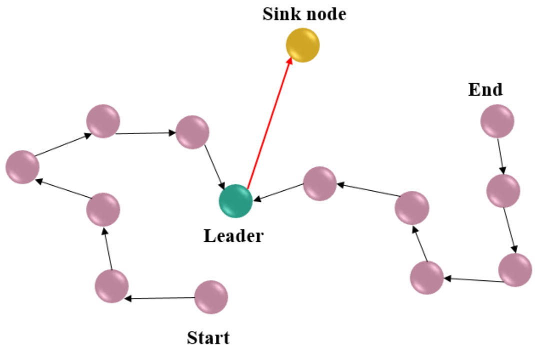

Fig. 9 PEGASIS Protocols in WSN

longer by delaying when the first node runs out of power. Each node, by comparing its energy with others, decides whether to act as a cluster head or not, so there's no need for all nodes to share energy details with neighbours. SEP tries to keep energy use balanced across the network, a figure that improves its stability and data flow compared to older methods [46].

However, managing the process can be challenging, particularly when ensuring that every node can take part. Additionally, nodes must frequently update cluster heads on their energy levels, which can sometimes add effort and reduce system efficiency [46].

4.1.6. HEED (Hybrid Energy-Efficient Distributed clustering)

Hybrid Energy-Efficient Distributed Clustering (HEED) was proposed in 2004. Figure 10 enhances scalability and lessens the need for excessive communication by enabling nodes to determine autonomously whether they will serve as cluster heads based solely on local knowledge. By choosing cluster leaders according to energy levels, the protocol helps the network last longer by prioritizing nodes with more energy left. Furthermore, the protocol guarantees that the clustering process is completed in a restricted number of steps, which makes it effective and adaptable to changing circumstances.

A drawback of the protocol is that it ignores node distribution, which may result in unequal energy consumption and poorly constructed clusters in networks with asymmetrical topologies. Even though individual nodes don't need to communicate much, bigger networks' performance can still be affected [47].

4.1.7. LEACH-TL (Two-Level Low-Energy Adaptive Clustering Hierarchy)

State that TL-LEACH uses a two-level clustering method in which nodes are arranged into clusters with appointed cluster heads (CHs) in charge of overseeing data transmission to the base station. Energy Efficiency: TL-LEACH greatly increases the network's operational lifetime by distributing the energy burden evenly among nodes and providing equal chances for CH selection [55] [56]. Demonstrate that TL-LEACH works better than traditional LEACH, with a 50% increase in operational rounds before node depletion and a network lifespan improvement of up to 60% [56] [57].

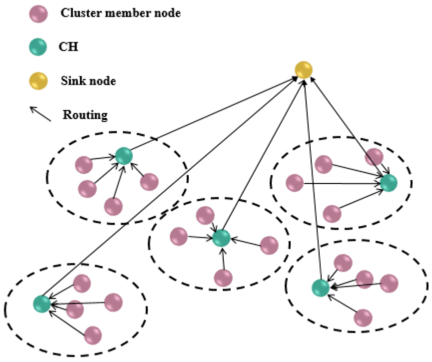

Fig. 10 PEGASIS Protocols in WSN

4.2. Enhanced LEACH Protocols

Researchers have enhanced the LEACH protocol to address its limitations and improve wireless sensor network performance. The traditional LEACH protocol faced issues with energy efficiency, cluster head selection, and data transmission [48]. Enhanced versions incorporate factors such as energy, distance, and density in cluster head election and utilize optimized routing algorithms for data transmission [49]. These improvements have resulted in significant gains, including increased network lifetime.

4.2.1. I-LEACH (Improved Low-Energy Adaptive Clustering Hierarchy)

To overcome the problem of randomness in Cluster Head (CH) selection, the researchers introduced an improved LEACH (I-LEACH) protocol for WSNs, which divides the network into zones with advanced and regular nodes. The protocol involves distributing SN and setting a new threshold for cluster heads. The data is maintained using a trust function for accurate capture.

An energy model is used to minimize wasteful energy transfer. The new CH selection technique removes uncertainty in the selection process. Cluster heads are chosen to maximize the remaining energy of the SN while decreasing the distance to the base station. The revised threshold reduces energy depletion in cluster heads and addresses low-node energy issues, resulting in reduced energy usage and improved system performance [50].

4.2.2. LEACH-C (Centralized Low Energy Adaptive Clustering Hierarchy)

Clustering is managed via the centralized method LEACH-C at the BS. The stable state doesn't alter even when every node participates in the Leach-C startup process. The base station transmits location information and signal strength. Therefore, less energy is required for data transmission when the network's global data of upgraded clusters is applied [51]. GPS or another location-tracking device is what you should utilize. The hub should provide the nodes with adequate power to cast votes for the cluster leader. All connected devices receive the data from the base station [51].

4.2.3. LEACH-M (Mobile Low Energy Adaptive Clustering Hierarchy)

By adding node and cluster head (CH) mobility, the LEACH-M protocol improves on the conventional LEACH framework and maximizes data relay to the base station (BS). In WSNs, where network lifetime and energy efficiency are critical, this adaptation is essential. The use of CH dynamics and node movability in LEACH-M is described in depth in the following sections.

LEACH-M allows nodes to move strategically, which can reduce the distance to the BS, thereby minimizing energy consumption during data transmission [52]. The protocol considers the surplus energy of mobile nodes, ensuring that nodes with higher energy levels are prioritized for data transmission, enhancing overall network efficiency [53].

In LEACH-M, CHs are selected based on their energy levels and proximity to the BS, which helps in maintaining a balanced energy load across the network [54]. By integrating mobility and dynamic CH selection, LEACH-M significantly reduces packet loss and energy consumption compared to traditional LEACH protocols [52].

4.2.4. LEACH-V (Vice Low Energy Adaptive Clustering Hierarchy)

V-LEACH offers many benefits as an improved version of the LEACH strategy. It is common knowledge that the energy of the cluster leader depletes more quickly than that of the regular nodes because it is responsible for collecting data from the ordinary nodes and transmitting it to the monitoring station. As a result, it will stop working before the rest of the cluster and render the whole thing useless because it cannot talk to the central node. To prevent such an occurrence, this method was put in place. When a CH dies, its responsibilities are taken on by a successor. The network always works well since all information is sent to the command center. When the vice-CH passes away, this protocol does not resolve the problem [58].

Table 3 lists the advantages and disadvantages of each hierarchical routing protocol covered in this study to give a thorough summary. This comparison can be used to comprehend the trade-offs between complexity, scalability, and energy efficiency.

Table 3: Comparative Analysis of Hierarchical Routing Protocols

Protocol	Strength	Weaknesses
LEACH [40].	Minimizes the energy consumption by selecting CHs periodically, which is simple and effective for small and medium-sized networks.	Random CH selection can lead to unbalanced energy dissipation, not suitable for large networks.
TEEN [43].	Optimal for time-sensitive applications and reduces needless transmissions via hard and soft thresholds.	Data can be lost if thresholds are not reached, and they are hard to manage because of two different thresholds.
APTEEN [44].	Combines periodic and event-driven data transmission for multiple purposes.	More sophisticated network management and possible delays in data transmission.
PEGASIS [45].	Forms chains to save energy and prolong the life of the network by reducing long-distance transmission.	It takes a long time for data to pass along the chains, and the end nodes consume energy irregularly.
SEP [46].	Ensures energy balance by taking into account the residual energy levels and maximizes network lifetime by delaying node failure.	Needs constant updates of node energies and a sophisticated CH selection process.
HEED [47].	Scalable, reduces communication overhead, prioritizes nodes with higher energy for CH selection.	Ignores node distribution, which leads to unbalanced energy consumption and performance degradation in large networks.
I-LEACH [50].	Enhances CH selection based on energy and distance and minimizes energy loss in CHs.	Requires complex node deployment and trust functionality, additional to the traditional LEACH.
LEACH-C [51].	Selecting a central node saves energy and utilizes less energy when transmitting data.	It requires GPS or location-based tracking devices; it does not apply to dynamic networks.
LEACH-M [52].	Uses mobile nodes to minimize energy usage and balances the energy load uniformly across the network.	Extra complexity from dealing with movement and possible packet loss in mobile networks.
LEACH-TL [55][56].	Two-level clustering improves energy efficiency and network lifetime by 50-60%.	It is a more complex clustering process and requires more computer resources.
LEACH-V [58].	Introduces vice-CH to handle CH failure and improves network reliability.	Fails to address vice-CH failure and increases overhead due to vice-CH management.
DEEC [59].	Suitable for heterogeneous networks, considers residual energy in CH selection.	Needs regular energy updates and a complicated CH selection process.
LEACH-F [51][62].	Fixed clusters reduce the re-clustering overhead and provide stable network performance.	Does not accommodate network changes like addition or failure of nodes) and is less flexible in dynamic situations.

4.3. Energy Distribution Protocol

Energy distribution protocols in WSNs help save energy and make the network last longer. They share tasks like sending and processing data among all nodes to avoid draining one node too fast. Protocols like LEACH and TEEN use clusters with a leader that changes often to balance energy use. This is important for keeping the network running, especially in hard-to-reach places.

4.3.1. DEEC (Distributed Energy Efficient Clustering Protocol)

In [59], the authors proposed the Distributed Energy Efficient Clustering Protocol for Heterogeneous Wireless Sensor Networks (DEEC). This is a two-level clustering protocol for heterogeneous WSNs. DEEC considers two types of nodes: normal nodes, which have initial low energy, and advanced nodes equipped with higher initial energy levels. DEEC uses initial and residual energy levels of nodes to select the CHs. This selection is based on the probability of the ratio between the residual energy of each node and the average energy of the network [60].

4.4. Hybrid and Advanced Protocols

LEACH-F (Fixed number of clusters in Low-Energy Adaptive Clustering Hierarchy). In this protocol, it creates clusters and selects CH centralized, the LEACH-F protocol (fixed number of clusters-LEACH) functions similarly to the LEACH-C approach. There is no re-clustering stage because clusters do not vanish at the start of each era. The position of the CH moves, but not the cluster itself. Furthermore, the steady phase does not affect the LEACH approach [61].

The main advantage of this method over LEACH is the elimination of the need for cycle-to-cycle initialization. LEACH-F creates clusters using a centralized approach, just like LEACH-C. One disadvantage of LEACH-F is that its fixed clusters do not respond to network changes, like the addition of new nodes or the loss of existing ones. The LEACH-F protocol preserves the previously formed clusters across the network, thus avoiding the time-consuming process of re-clustering [51] [62].

Table 3 provides a summary comparison between various hierarchical routing protocols in Wireless Sensor Networks (WSNs), highlighting their advantages and disadvantages. LEACH is a widely used protocol that selects cluster heads regularly to reduce energy usage. However, its random selection can lead to uneven energy distribution. LEACH has evolved with LEACH-C, LEACH-M, LEACH-TL and others to enhance energy efficiency, node mobility, and network longevity through centralized cluster head selection.

TEEN and APTEEN protocols are useful for time-sensitive applications due to their use of hard and soft thresholds but may cause data loss due to their complicated management. PEGASIS data transmission is done through chains, reducing energy usage but increasing latency. SEP, HEED, DEEC, and I-LEACH focus on optimizing cluster head selection based on remaining energy levels, extending the network's lifespan. Hierarchical clustering-based protocols enhance energy efficiency and network management, but there's a need for more adaptable solutions for wireless sensor network changes.

5. DISCUSSION

Hierarchical routing protocols are important for saving energy and improving scalability in WSNs. As shown in Table 3, Protocols such as TEEN and APTEEN are well-suited for time-sensitive applications due to their threshold-based data transmission. However, their reliance on hard and soft thresholds can result in data loss if conditions are not met, and their management complexity increases with network size. But PEGASIS, which is a well-known protocol that builds on LEACH by forming chains of sensor nodes instead of clusters, reduces energy use and extends the network’s life [45]. While PEGASIS works well in many cases, it has some challenges that make it less effective in real-world situations.

Table 2, summarizes The performance metrics of various hierarchical routing protocols, which highlights the network lifetime and residual energy at round 500. This comparison demonstrates the trade-offs between energy efficiency and network longevity across different protocols.

One big issue is the delay caused by passing data through the chain. This makes PEGASIS unsuitable for applications where data needs to be delivered quickly, such as emergency detection. PEGASIS faces challenges in maintaining network connectivity and data integrity in the presence of node failures or mobility-induced disruptions. Ensuring fault tolerance and resilience against unpredictable events is crucial for the robust operation of WSNs, especially in dynamic environments. Also, energy use is uneven because nodes at the end of the chain use more energy for repeated transmissions, causing them to die faster and reducing the network’s lifespan [63].

To solve these problems, improvements can be made. For example, using parallel data transmissions or breaking the network into smaller chains could reduce delays. Allowing nodes to form chains locally would make the protocol easier to use in large and dynamic networks. To balance energy use, selecting leader nodes based on their energy levels or sharing the workload among nearby nodes could help.

In short, PEGASIS is a strong starting point for energy-efficient routing, but fixing its issues can make it more practical and useful. Improving it would allow PEGASIS to work better in more types of networks and handle more demanding tasks.

6. CONCLUSION

This paper has explored the importance of hierarchical routing protocols in wireless sensor networks, with a particular focus on PEGASIS (Power-Efficient GAthering in Sensor Information System). PEGASIS is known for its ability to reduce energy consumption and enhance the lifespan of a network by organizing sensor nodes into clusters. This structure allows for more efficient data gathering and communication within the network, making it a promising protocol for large-scale applications.

However, despite these advantages, PEGASIS faces several challenges. One of the primary issues is the efficient management of cluster formation and cluster selection, as well as balancing the energy load among sensor nodes. These challenges become more difficult when the network size increases, hence affecting the overall performance and scalability of PEGASIS in large environments.

In summary, even though PEGASIS offers a practical way to route sensor networks with minimal energy use, much more may be done. Understanding its full capabilities and ensuring that it is popular in practical applications would require addressing its present limits through additional study and development.

7. FUTURE DIRECTIONS

Network lifetime and energy saving is good with PEGASIS, but we still have many problems. These issues need to be optimized for better performance, particularly in large, dynamic WSNs. A major pain point is building and managing clusters. Currently, PEGASIS communications utilize a static chain.

As a result, certain nodes (especially those at the end) consume more energy than others. Researchers should come up with new methods in the future so nodes can create small groups or chains based on the real situation of the network.

Another critical improvement to this protocol is how to choose the leader and load balancing. Right now, PEGASIS picks the leader in turns without checking how much energy each node has. This makes some nodes lose power too fast. In the future, new methods should choose leaders based on energy left in the node so energy can be shared more equally in the network.

Finally, new technology like machine learning (ML) and energy harvesting can make PEGASIS better. Machine learning can help check the energy of nodes, network traffic, and the best way to send data. This can help make better decisions for chain making and leader choosing.

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مراجعة بروتوكولات التوجيه الهرمية في شبكات الاستشعار اللاسلكية: الأنواع والتطورات الأخيرة

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الملخص

تُعد شبكات الاستشعار اللاسلكية (WSNs)ضرورية في تطبيقات مثل المراقبة البيئية والرعاية الصحية والمدن الذكية. ومع ذلك، قد تواجه موارد الطاقة المحدودة لعقد الاستشعار والتطبيق بعض المشكلات الحرجة عند نشر أعداد كبيرة من عقد الاستشعار فيما يتعلق بنقل البيانات بكفاءة. في السابق، اعتمدت شبكات الاستشعار اللاسلكية على بروتوكولات التوجيه المستوية والبروتوكولات القائمة على الموقع لنقل البيانات، ولكن المشكلة الرئيسية في بروتوكولات التوجيه المستوية هي أنها تعمل بشكل غير فعال على شبكة كبيرة الحجم. وتؤدي نتائج الاتصالات المباشرة بين جميع العقد إلى ارتفاع استهلاك الطاقة الازدحام. وقد أدت هذه المشاكل إلى تطوير بروتوكولات التوجيه الهرمية، وذلك لمعالجة هذه المشاكل من خلال تنظيم العقد في مجموعات، وبالتالي تقليل استهلاك الطاقة وتحسين قابلية الشبكة للتوسع. وهذا يقلل من عبء الاتصالات ويطيل عمر الشبكة. تستعرض هذه الورقة الاستعراضية التحديات التي أدت إلى تطوير بروتوكولات التوجيه الهرمي HRPs والتطورات الأخيرة التي تم إجراؤها لبروتوكولات التوجيه الهرمية، مع التركيز على بروتوكولات التوجيه الهرمي ذات الكفاءة في استهلاك الطاقة في نظم معلومات الاستشعار (PEGASIS) .تقدر الحلول التي تقدمها هذه البروتوكولات وتدرس التحديات المتبقية، مثل إدارة المجموعات الديناميكية وموازنة الأحمال. ونتيجة لذلك، يحسّن بروتوكول (PEGASIS) كفاءة الطاقة وقابلية التوسع إلى حد كبير، ولكن لا تزال هناك ثغرات للتحسينات المحتملة. لذا ستكون هناك حاجة إلى بذل جهود بحثية في هذه المجالات من أجل تحقيق أقصى قدر من الأداء وقابلية التطبيق لبروتوكولات التوجيه الهرمي في الشبكات العالمية لمجتمع المعلومات.

الكلمات الداله:

شبكات الاستشعار اللاسلكية(WSNs)؛ بروتوكولات التوجيه الهرمي (HRPs)؛ كفاءة الطاقة؛ LEACH؛ PEGASIS؛ التوجيه القائم على المجموعات.