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COMPARATIVE ANALYSIS OF ENERGY EFFICIENT HIERARCHICAL ROUTING PROTOCOLS IN WIRELESS SENSOR NETWORKS

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Abstract

Wireless Sensor Networks (WSNs) relies on the efficiency of routing methods or techniques to maintain fast and reliable data transmission where as preserving limited node batteries. Hierarchical routing techniques are universally used due to their ability to break sensors network into cultures. I this mechanism sensor can communicate with clusters head.ad, after that the cluster head send data in consolidated or aggregated form to the base station. This is a layered communication model which significantly reduces the energy consumption and supports large scale scalability. There are different challenges which are related to energy optimization and extended the network lifetime continue to overcome issues in WSN design. This paper presents a detailed comparative analysis of major energy-efficient hierarchical routing protocols, including LEACH, TEEN, PEGASIS, HEED, APTEEN, LEACH-VF, LEACH-C, LEACH-SC, LEACH-M, LACH-EP, SEP, MIEEPB, DEEC, ESEECH, EARP, EHCR-FCM and EESNR. Each protocol is examined with respect to key performance indicators such as energy utilization, network stability, and lifetime improvement. The analysis reveals that while individual protocols offer specific benefits, no single approach fully addresses all performance requirements. Therefore, adaptive and hybrid routing strategies emerge as more effective solutions for enhancing overall network performance and network efficiency. This study provides a foundation for future research to develop intelligent and energy-efficient routing mechanisms for advanced Wireless Sensor Networks.

1. Introduction

There are numerous hierarchical routing protocols available for Wireless Sensor Networks (WSNs). The primary objective of this study is to perform a comparative analysis of these protocols. Energy efficiency is a fundamental requirement and the core design goal of WSNs, as sensor nodes are typically resource-constrained [1]. Initially, only a few protocols were proposed, such as Low Energy Adaptive Clustering Hierarchy (LEACH) [2], Threshold Sensitive Energy Efficient Sensor Network Protocol (TEEN) [3], Power-Efficient Gathering in Sensor Information Systems (PEGASIS) [4], Adaptive Threshold-sensitive Energy Efficient Network (APTEEN) [5], and Hybrid Energy Efficient Distributed Clustering (HEED) [6] were developed. However, over time, a large number of additional protocols have been developed to improve performance in terms of energy consumption and scalability [7]. Various researchers are still attempting to extend the lifetime of WSNs by minimizing the amount of energy that nodes consume. There are a number of new routing protocols over the years. Some are constructed from the ground up, some are just updated versions of older ones. The overall objective remains the same, namely to reduce energy consumption and improve the overall performance of the network [1,7]. This project is an attempt to research on the energy efficient hierarchical routing protocols in Wireless Sensor Networks. We created a comparison model that assesses the performance of these protocols in terms of energy efficiency, data aggregation, scalability, cluster stability, and load balancing. We also developed a comparison table in detail so that it would be easier to see the performance of each protocol compared to the others. This work may be useful to other researchers to learn what each protocol is good at and what it is not. It can also be useful to network engineers in making decisions on the protocol to be used in a given application. The table and conclusions in this paper offer some practical advice to anyone who wants to enhance the performance of a network or make sensor networks last longer.

2. Challenges in Wireless Sensor Networks

The sensor nodes are responsible for many issues related to WSNs. The nodes have limited energy, processing power and can only communicate with each other over short distances [1]. Of these problems, the most significant are energy efficiency and the ability of the network to continue operating.

a. Energy Efficiency:

Sensor nodes are typically battery-powered, and in many applications, replacing or recharging these batteries is impractical. Therefore, efficient energy utilization is essential to ensure sustainable network operation. A significant portion of energy is consumed during data transmission and reception, making communication protocols a key factor in energy optimization [2]. Energy-efficient routing protocols, particularly clustering-based approaches, aim to minimize redundant transmissions and balance energy consumption among node [7].

b. Network Lifetime:

These challenges are tightly coupled as the energy efficiency benefits will contribute to network longevity as well [1,7]. The overall lifetime of a WSN is dependent of the utilization of energy at each node. Some nodes consume way more energy than the others, the nodes that become 'failed' early split up the network and the overall performance of the network is reduced. The routing technique should also be flexible to adapt and distribute the load among the sensor nodes fairly to maintain the network for a longer time [6].

3. Literature Review

A new hierarchical routing protocol that is energy efficient was created to address issues in the previous protocols such as LEACH, PEGASIS, TEEN, and APTEEN. These older ones have a tendency to consume excessive energy, are not scalable, and have an uneven load distribution. The new approach takes place in two stages. The first phase involves creating a topology map of the network, which is done without the use of GPS, thus saving on cost and making things simpler. The second phase involves sleep and wake scheduling, load balancing between nodes, and data aggregation to reduce the energy consumption of the nodes and increase the network's runtime. The sensor nodes are also organized into teams, groups and zones for efficient communication and data transmission. The protocol was evaluated by TelosB IEEE 802.15.4 sensor nodes and NS-2 simulation. The results demonstrated that the energy consumption and network lifetime were significantly improved compared with other hierarchical protocols. The load was distributed more evenly and the energy loss in the network decreased. There was a minor drawback of a slight delay at the beginning due to the topology setup phase. Overall, the protocol worked well [8]. The other one was formulated with the idea of hierarchical clustering in order to save on energy consumption and keep the network alive. Uses sleep and wake strategy, and has a TDMA-based scheduling system in place. The idea is to reduce the energy loss when nodes are idle or sending data that they don't need to send. This setup ensures that the network works more efficiently and effectively, and that it operates in a reliable manner. Evaluation of the proposed approach is carried out by simulation under different scenarios to investigate the performance of the approach. Comparisons is carried out with the existing routing protocols such as LEACH, PEGASIS, and HEED with the help of efficient performance metrics of the system like throughput, packet delivery ratio, and end-to-end delay and energy consumption. The results indicate that the hierarchical clustering mechanism, combined with energy-aware scheduling, significantly enhances network performance. Scheduling of sleep also helps to save unnecessary energy since each node is active only when needed, which enhances better energy conservation. The protocol also shows better data transmission reliability and minimized overhead of communication than the conventional clustering-based methods. These enhancements underscore the success of the combination of clustering methods and adaptive routing algorithms in the optimization of WSN routing. [9]. Swarm intelligence is applied to develop an energy efficient hierarchical routing protocol in Wireless Sensor Networks (WSNs) to optimize the data routing process and increase the lifetime of the network. The suggested BeeSwarm model makes use of metaheuristic optimization that allows making adaptable and efficient routing choices. The protocol will be divided into three phases.: BeeCluster used to form clusters, BeeSearch to find routes and BeeCarrier to transfer data, which coordinates the work of the clustering, routing, and communication processes. Multi-phase architecture enhances the arrangement of the networks and enables the networks to optimize the use of resources. Swarm intelligence allows the dynamic choice of paths and load balancing minimizing the energy dissipation among sensor nodes. Key metrics used to perform the evaluation of performance include throughput, energy consumption, and the ratio of packet delivery. The comparison against the current swarm-based routing protocols indicates that it has a better performance in all the parameters of evaluation.

The efficient routing policy reduces energy consumption whilst ensuring high transmission of data that is reliable and consistent. Also, the swarm-based approach is adaptive and therefore scales better and is more robust under dynamic network environments. These results indicate that the integration of swarm intelligence with hierarchical routing significantly improves communication efficiency and extends the operational lifetime of WSNs [10]. MIEEPB is a routing protocol based on an improved version of PEGASIS and is mobile sink based. It was designed to gather data more efficiently and to make the network last longer. There are some obvious issues with the older protocols such as LEACH, PEGASIS, and TEEN. LEACH is not always able to select the best cluster heads. TEEN is not suitable for all environments. The building of chains between nodes is an additional communication overhead in PEGASIS.. The proposed approach incorporates a mobile sink to dynamically collect data from sensor nodes, thereby reducing transmission distance and balancing energy consumption across the network. This mobility-assisted mechanism minimizes communication delay and mitigates the formation of energy holes, which are common in static sink-based architectures. In addition, improved routing paths ensure more reliable data delivery and reduce the need for data to be transmitted multiple times. With the addition of a mobile sink, the results demonstrate that the energy consumption is reduced and the network remains more stable than with the old protocols. The data collection method also adjusts to evenly distribute the workload across the nodes without overloading any one node. This will allow the network to operate for a longer period of time. In general, the mobile sink appears to overcome many of the issues that traditional hierarchical protocols have with WSN configurations. [11]. This study investigates the energy efficient routing protocols in WSNs, especially those based on hierarchical and chain-based designs. Several routing strategies are compared and contrasted in terms of their construction and their performance, rather than selecting one best protocol. The energy consumption and the effectiveness of routing is studied using mathematical models. One of the good clustering protocols is LEACH, which elects cluster heads in a distributed way to aid energy management in the network. The choice of cluster head is crucial because it affects the utilization of the energy and network lifetime. On the other hand, energy-saving protocols like PEGASIS do so in a different manner. They carry information from one node to another in a chain, thus restricting the distance of the transmission. The comparison shows that the performance of a routing protocol is very much dependent on the network configuration, the number of nodes and the requirements of the application. Some protocols work better in some situations and not as well in others. When selecting a routing protocol for a WSN, you need to consider the constraints of the system, the goals you're trying to accomplish, and the characteristics of the network. There is no single solution for all situations [12]. This paper surveys some of the routing protocols employed in WSNs. It is about single-hop and multi-hop communication, and its operation in homogeneous and heterogeneous networks. The protocols that are studied are LEACH, SEP, HEED, EECS, UCS, DWEHC, TEEN, BCDCP and PEGASIS. They are all compared on a variety of factors such as scalability, end-to-end delay, energy consumption and load balancing. The evaluation highlights the strengths and limitations of different routing strategies depending on the network conditions. Multi-hop and hierarchical methods tend to save

more energy than flat routing because nodes do not have to send data as far and data gets combined along the way. Clustering protocols help too because the work is split between cluster heads, so energy use stays more even across the network. How well a routing protocol performs really depends on the network layout, how many nodes are in it, and what the application needs. Picking the right routing method matters a lot if you want good communication and a longer network life. From what the analysis shows, clustering and hierarchical approaches seem to work better than most other options for energy-efficient communication in WSNs. [13]. An enhanced hierarchical routing protocol, termed ESEECH (Enhanced Scalable Energy Efficient Routing Protocol), is developed to improve energy efficiency and communication performance in Wireless Sensor Networks (WSNs). This protocol is an improvement over the previous hierarchical protocols, and incorporates a more efficient selection of relay nodes for data forwarding and energy efficiency. It was evaluated with other protocols such as LEACH and SEECH for various performance metrics such as throughput, average energy consumption and packet delivery ratio. The results indicated that it is more energy efficient and communication is more reliable. Relay nodes are used appropriately, which means that energy is distributed more evenly and nodes are not dying too early. The protocol also performs better and is more resilient in the face of network changes. It also reduces communication overheads, as the routing paths are configured in a more intelligent manner. In summary, ESEECH is a good routing solution for WSNs with limited resources that are energy-aware. [14]. A power-efficient hierarchical routing protocol is developed for Wireless Sensor Networks (WSNs) to enhance centralized control and optimize energy management. This is controlled by the base station which is aware of the entire network. That includes the topology and the amount of energy that each node has remaining. All that information can help the base station make better routing decisions. The data is transmitted through the cluster heads and intermediate nodes via the optimal path. The energy efficiency and performance of the network were compared with LEACH-C using MATLAB simulations and the results indicated that it consumes less energy and the network has better performance. The coordination mechanism is centralized, which guarantees equal energy consumption, minimizes overhead in communication and improves reliability of data transmission. The above properties suggest centralized energy-aware routing is a more effective centralized solution to the hierarchical communication in resource-constrained WSN settings. [15]. These comparative studies are done on energy efficient hierarchical routing protocols in the wireless sensor networks (WSNs) in the context of agricultural irrigation system under the heterogeneous network condition. Several protocols such as LEACH, TEEN, SEP, and EAMMH are tested through simulations in MATLAB with mathematical modeling to test their performance. The important evaluation metrics would include network lifetime, remaining period of stability, throughput, the number of cluster heads per round and the number of dead nodes and would be examined comprehensively. The findings reveal that TEEN has a better network lifetime whereas SEP has a better throughput performance as compared to other protocols. This analysis also shows that the efficiency of the protocols greatly depends on the node heterogeneity, energy distribution, and the traffic patterns in the network. These results underscore the idea that various routing protocols are more or

less efficient based on application specific needs, as well as network peculiarities. These observations highlight the relevance of choosing routing strategies according to the performance-based criteria in order to optimize the use of energy, increase the scalability and efficiency of communication in the heterogeneous WSN environment. [16]. The met heuristic strategy was suggested based on computational intelligence approach to the improvement of the lifetime of the wireless sensor networks (WSNs) due to the alarming problem of energy drainage of the sensor nodes. The paper is based on the prior research, combining the ideas of more advanced hierarchical routing methods and optimization strategies. The suggested approach focuses on the effective clustering and adaptive routing to enhance the overall network performance. The main characteristics of the approach are self-organization of nodes, a multi-phase structure to cluster, create routes and transmit data. The simulation tools were used to conduct the performance evaluation and consider metrics like power consumption and packet delivery ratio. The results demonstrate that the proposed method effectively reduces energy consumption while maintaining reliable data communication. Additionally, These findings reveal that the suggested approach is efficient in terms of lowering energy usage and still ensuring the reliable data transmission. Also hierarchical and smart routing plan is a factor in enhanced network stability. Computational intelligence and structured routing combine to achieve scalability and adaptability. In general, the suggested solution is an efficient way of prolonging the network life in WSNs [17]. This is because a new routing algorithm was proposed to be used in WSNs and it can be used in both hierarchical and flat configuration. The paper notes that the quality of a WSN performance actually depends upon the quality of the routing protocol. This approach involves selecting some nodes as cluster heads to process data in their clusters. Within each cluster, multi-hop communication is employed, avoiding the need for nodes to transmit data across long distances and conserving energy. The cluster heads then gather and fuse the data and send it to the base station. There are two strategies used for communication within the clusters. The first one is the "philanthropist" approach, which means that nodes with higher residual energy are selected first. The second is the "selfish" approach, which selects the closest node rather. The combination of both options provides greater flexibility in the network depending on the network's needs. This algorithm was found to be very energy efficient through simulations and yet still sent data efficiently. It was also able to deal with larger networks and adapt to changing circumstances. So it appears to be a good choice for energy conscious routing in WSNs. [18]. One research was conducted on LEACH as a basic clustering protocol for WSNs and concluded that it consumes relatively low energy. It has been evaluated in OMNeT++ simulation environment to understand its performance in terms of energy consumption and network stability. The operation of LEACH is that the cluster head role is rotated among all the nodes so that each node has a chance to be the cluster head. This ensures a more even energy usage and extends the life of the network. However, there were some issues identified in the study. In some cases, the cluster heads are concentrated in a particular part of the network and some nodes are isolated from the cluster head. In such a case, communication deteriorates and the network does not function as well. The study recommended the need to make changes in the selection of cluster heads to address these problems. Overall, while LEACH provides a strong baseline for energy-efficient routing, further

enhancements are required to improve its adaptability and performance in diverse network scenarios [19]. The comparison of energy-efficient routing protocols of wireless sensor networks (WSNs) was done in terms of LEACH, PEGASIS, and TEEN. The research notes that there are many routing protocols that have been designed to minimize power usage and to maximize network lifetime. LEACH uses clustering-based design where the network is partitioned into clusters that are controlled by a cluster head that performs data aggregation and transmits the information to the base station. Such local coordination reduces communication overhead, energy consumption by enabling short-range transmissions. PEGASIS, in contrast, has a communication model that is based on chains: each node can communicate with its neighboring nodes and one node transfers the sum of the data to the base station. This will decrease the number of redundant transmissions, but can cause delays in communication. In TEEN, a hierarchical clustering mechanism is used with multi-level data transmission, which means that data is transmitted to the base station via successive cluster heads. This multi-level communication can lead to higher energy use in some cases, however. The study offers some insights into the strengths and weaknesses of these protocols in terms of energy efficiency and communication structure. In general, the analysis highlights the trade-offs between the use of suitable routing protocols for various WSN applications. [20]. The performance analysis of hierarchical routing protocols for wireless sensor networks (WSNs) was carried out by comparing the classical hierarchical routing protocols LEACH, PEGASIS, and TEEN with their enhanced versions with spatial correlation, namely SCLEACH, SCPEGASIS, and SCTEEN. The study proposes a hierarchical routing protocol, named spatial correlation-based hierarchical routing protocol (SCHRP), which uses clustering techniques to enhance the energy efficiency and network performance. The enhanced protocols will be used to overcome the deficiencies of the conventional protocols taking advantage of spatial correlation to transfer data effectively. The performance was measured using the different parameters such as throughput, packet drop, end to end delay and the ratio of packet delivery. The SCHRP proposed protocol was also analysed using K-D tree algorithm and simulated using a network simulation tool. The findings indicate that SCHRP is better than the traditional protocols, as it has increased communication efficiency and reduced packet loss. The protocol shows about 6.35% more energy efficient than LEACH in particular. Spatial correlation also enhances aggregation of data and reduces unnecessary transmissions. The suggested solution is more efficient and scalable routing solution of WSNs in general.[21]. An energy efficient comparison of routing protocols of wireless sensor networks (WSNs) was done with reference to LEACH and PEGASIS. The comparison of the benefits and shortcomings of both protocols is done through MATLAB-based simulations. LEACH is characterized by low computational complexity, reduced communication overhead, and the use of local data aggregation to minimize energy consumption. It has, however, some drawbacks including higher delay, dependence on global network knowledge and lower adaptability to dynamic network topologies. On the other hand, PEGASIS uses a chain-based communication mechanism and uses optimization techniques like Ant Colony Optimization (ACO) to reduce the distance of communication. This helps to balance the energy of the nodes and prolong the network's life. In addition, PEGASIS eliminates redundant transmissions by creating efficient communication

chains. However, it demands the base station to keep track of the energy levels of nodes, which can complicate the system. The simulation results show that PEGASIS is more energy efficient than LEACH. In summary, the study points out the pros and cons of clustering and chain based routing strategies in WSNs. [22]. An energy-efficient hierarchical clustering and routing protocol based on Fuzzy C-Means (EHCR-FCM) was proposed for wireless sensor networks (WSNs) within the context of Internet of Things (IoT) applications. The study emphasizes that energy consumption in WSNs is highly dependent on routing strategies and clustering techniques. The proposed protocol is based on three-level hierarchical structure, with the cluster formation based on the grid centroids, inter-node distances and residual energy level. Dynamic clustering and grid-based organization is used to maximize energy usage and enhance routing efficiency. The cluster heads (CH) and grid heads (GH) are selected based on a fitness function which takes into account the energy of the nodes and spatial properties. This will help to distribute energy evenly throughout the network. The performance evaluation shows that the proposed protocol consumes much less energy than the existing protocols. Moreover, it can improve the stability and efficiency of the routing process, thereby extending the lifetime of the network. In general, the EHCR-FCM protocol is an intelligent and adaptive protocol for energy-efficient communication in WSN based IoT environments. [23]. An energy-efficient routing protocol was proposed for large-scale wireless sensor networks (WSNs), particularly targeting irrigation and agricultural monitoring applications. The paper presents the paramount importance of sensor nodes in the environment data gathering, and the significance of effective routing schemes in increasing the network lifespan. The proposed protocol will deal with the drawbacks of the current methods like LEACH, I-LEACH and M-LEACH by providing better energy-conscious routing schemes. It is specifically created to work with large scale deployments, with increased scalability and reliability. The assessment of energy consumption and network efficiency involved performance evaluation with the help of NS-3 simulation environment. The findings show that the suggested protocol would have a much better performance than current approaches. Specifically, it has been shown to be nearly 27.8% more energy efficient. This will help in increasing the life of the network. In general, the developed solution offers an effective and strong solution to WSN-based irrigation systems. [24]. EEHCM (Energy Efficient Hierarchical Clustering Mechanism) was an improved hierarchical clustering mechanism that was suggested to tackle the highly burning problem of energy depletion in wireless sensor networks (WSNs). The paper underlines the fact that it is not always feasible to replace or recharge sensor node batteries and therefore energy-efficient routing is required to ensure sustainability of the network. The protocol suggested is better in terms of the selection of the cluster heads as it takes into account distances to the sink, residual energy, and communication cost. This multi-criteria method allows conducting clustering more efficiently and with balanced energy usage on the network. The protocol hierarchy makes the routing functions easier and minimizes the overhead of communication. This was compared to the LEACH protocol to determine performance improvements. The outcomes of the simulation in graphical and tabular analysis indicate that the energy consumption of the backbone and communication energy has significantly decreased. Moreover, the suggested method is the most efficient use of resources to enhance network

lifetime. To conclude, the EEHCM scheme is a good scheme and it is designed in such a way that it can address the routing problem of WSNs which are energy saving. [25]. A comprehensive analysis of low-power routing protocols for wireless sensor a network (WSNs) in aquatic environments was presented, emphasizing the critical role of energy efficiency in such deployments. The study examines various LEACH-based protocols, including W-LEACH, T-LEACH, LEACH-RA, LEACH-F, LEACH-EA, LEACH-EP, LEACH-EE, LEACH-M, LEACH-C, and LEACH-HRP. These protocols were analyzed in terms of their advantages and limitations under water-based communication conditions. The results emphasize the importance of the performance impact of routing protocols in WSNs due to the environmental factors. The study focuses on the most important challenges of energy use and the reliability of communication in such situations. Based on comparative evaluation, LEACH-EP has been found to have better energy efficiency. This protocol works well to save energy and still provide reliable data transmission. Besides, it is a dynamic species to underwater conditions. The overall result of the analysis is that LEACH-EP is the most appropriate protocol from the analyzed ones for the energy efficient routing in water based WSN applications.[26]. A new energy efficient routing scheme based on geographic and hierarchical techniques and mobile sink was proposed for wireless sensor networks (WSNs) in large scale IoT applications. The paper highlights the importance of efficient energy consumption as it is a key demand of the sensor nodes with limited power. The proposed approach involves hierarchical clustering and location based routing in order to optimize data transmission and minimize the communication overhead. The addition of a mobile base station provides further energy efficiency by reducing the amount of long-range transmissions. This way, load is distributed and energy is saved throughout the network. The performance evaluation was carried out through a simulation-based analysis, with the consideration of useful metrics of packet delivery ratio and end-to-end delay. The results show that the proposed approach is more efficient and reliable in the communication aspect as compared to the existing routing algorithm.. Additionally, the protocol significantly improves residual energy levels among sensor nodes. It is reported that the proposed approach increases network lifetime by approximately 23.68%. Overall, the method provides an effective solution for energy-efficient routing in large-scale WSN deployments [27]

4. Data Anaysis

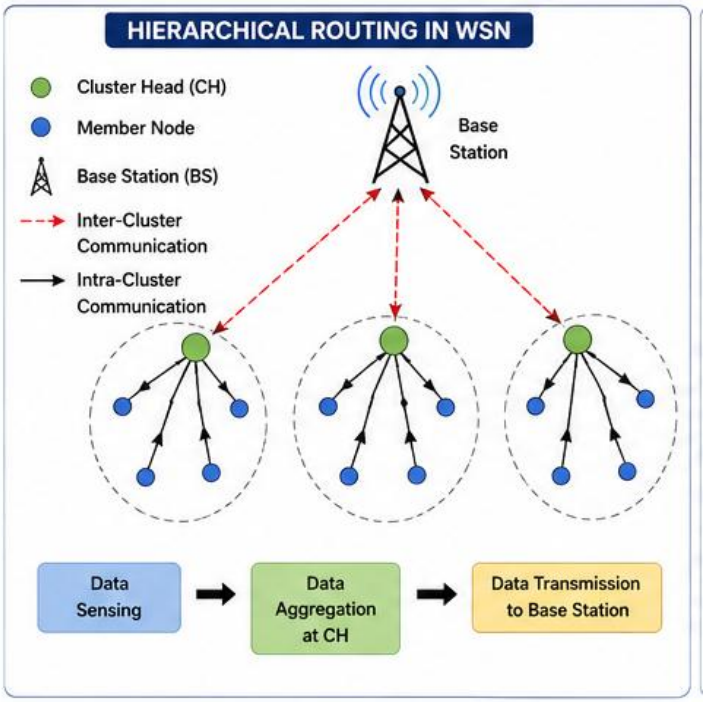

Figure 1

Figure 1 illustrates the fundamental architecture of hierarchical routing in wireless sensor networks (WSNs). In this model, sensor nodes are organized into clusters to enhance communication efficiency and reduce energy consumption. There are cluster head (CH)s who are responsible for managing activities within clusters. The member nodes use short-range communication to transmit sensed data to the concerned CH. The CH aggregates and fuses the data to remove data redundancies and compress the data. After aggregation, the aggregated data is sent to the base station (BS) by long-range transmission. Individual nodes have a greatly reduced communication overhead in this hierarchical structure. This reduces the direct transmissions to the BS and thus saves energy at the nodes. The separation of roles between CHs and member nodes promotes the organization of the network. There is also the consideration of scalability in the strategy where the network can be expanded in phases without compromising on the performance. Moreover, rotation of CHs can be periodically introduced, to evenly distribute energy consumption across the nodes. This will prevent untimely network failure of nodes and extend network life. The model is particularly relevant where the deployment is on a large scale. Overall, hierarchical routing provides a systematized and energy aware communication paradigm.

COMPARISON OF ENERGY EFFICIENT HIRRACICAL ROUTING PROTOCOLS

Protocol	Energy Efficiency	Load Balancing	Data Aggregation	Scalability	Cluster Stability	Heterogeneous Networks
LEACH	High	Normal	Yes	High	Normal	No
TEEN	High	Normal	Yes	Low	High	No
PEGASIS	High	Normal	No	Low	Low	No
HEED	Normal	High	Yes	Low	Normal	Yes (limited)
APTEEN	Normal	Very Low	Yes	Low	Low	No
LEACH-VF	Normal	High	Yes	Normal	High	No
LEACH-C	High	High	Yes	Low	High	No
LEACH-SC	Normal	Normal	Yes	Low	High	No
LEACH-M	High	High	Yes	High	Normal	No
LACH-EP	High	High	Yes	High	High	Yes
SEP	High	High	Yes	High	High	Yes
MIEEPB	High	High	Yes	High	High	Yes
DEEC	High	High	Yes	High	High	Yes
ESEECH	High	High	Yes	High	High	Yes
EARP	High	High	Yes	High	Normal	Yes
EHCR-FCM	High	High	Yes	High	High	Yes
EESNR	High	High	Yes	High	High	Yes

High / Yes | Normal | Low | Very Low / No

Table 1

A comparative analysis of different energy efficient hierarchical routing protocols on Litterer Review section is shown in Table 1. The protocols are evaluated based on different performance metrics like energy efficiency, load balancing, data aggregation, scalability, cluster stability and heterogeneous network support. The tabular presentation allows simply and systematically comparing all the chosen protocols. Classical protocols such as LEACH and PEGASIS have good energy efficiency, but lack in scalability and heterogeneity support. Other advanced protocols like DEEC, EHCR-FCM and MIEEPB, in turn, are always high-performing on a majority of the parameters. To highlight the flexibility of modern protocols in realistic deployments, the heterogeneity support is included. The table also shows how routing strategies have developed, initially with simple clustering strategies, then to more intelligent and balanced routing. The variations in load balancing and cluster stability indicate energy distribution variations. Most protocols have data aggregation, and it is crucial in minimizing communication overhead. The protocol compares and contrasts the strengths and weaknesses of the protocols. It can also be used as a source of choosing appropriate routing strategies. The table gives a comprehensive picture of protocol performance, in general.

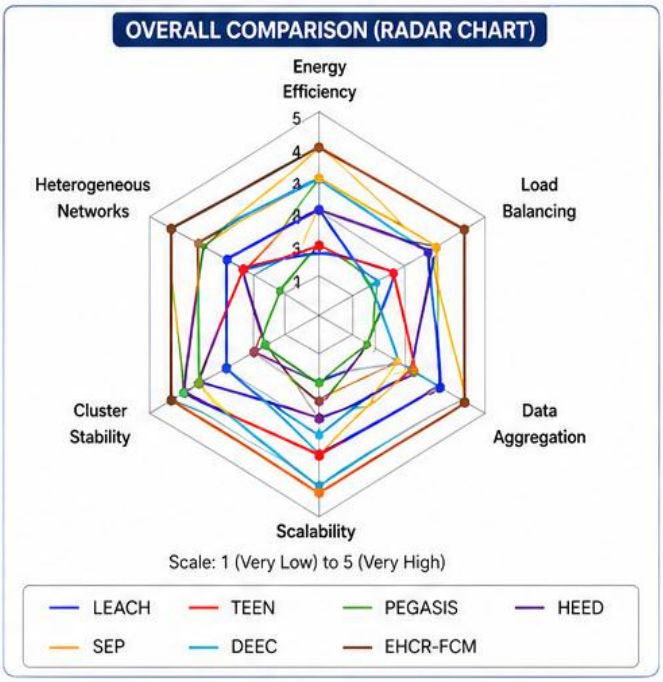

Figure 2

Figure 2 depicts a radar chart illustrating the multi-dimensional performance comparison of selected routing protocols as shown in Table1. The axes of the chart correspond to different evaluation parameters: energy efficiency, scalability, load balancing, cluster stability and heterogeneity support. The graphical format allows for multiple metrics to be displayed at once. Protocols like DEEC, SEP, and EHCR-FCM show bigger and more symmetrical coverage areas, which suggest well-balanced and much better performance. On the other hand, protocols, such as PEGASIS and TEEN, show sporadic and constrained coverage, due to performance compromises. The radar chart is a good way to visually show the pros and cons of each protocol in one glance. It allows a comparison to be made easily without too much numerical analysis. A high uniformity of the shape of the polygon indicates a consistent performance in the parameters. As seen in above pie chart, the modern WSNs scenarios are indeed being dominated by the use of advanced protocols. It gives an understanding of the different protocols' focus on certain metrics. This will be useful in multi-objective optimisation in particular to determine the best protocol. It gives more sense in the context of comparisons. The radar chart, in general, is a good analytical tool.

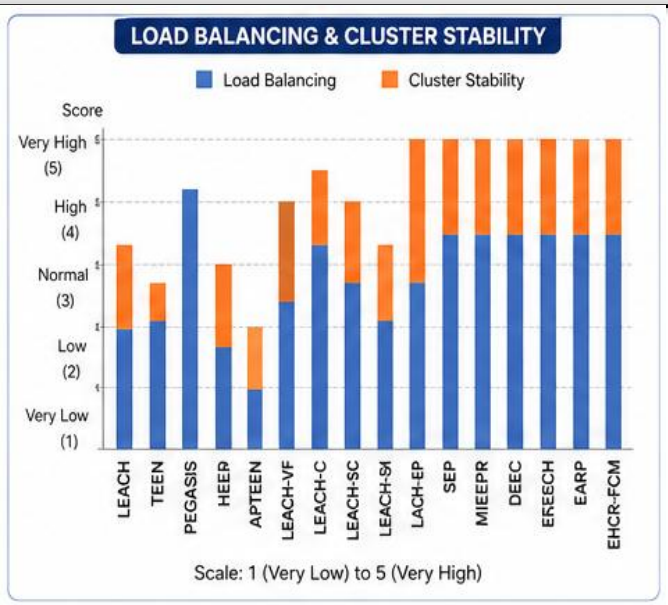

Figure 3

Figure 3 presents a bar chart comparing routing protocols as shown in Table1 based on load balancing and cluster stability. Load balancing refers to the equitable distribution of energy consumption among sensor nodes. Effective load balancing prevents the rapid depletion of specific nodes, thereby enhancing network longevity. Cluster stability, on the other hand, indicates the duration for which clusters remain operational without frequent reconfiguration. High cluster stability reduces control overhead and improves communication efficiency. The chart demonstrates that protocols such as DEEC and EHCR-FCM achieve high values in both metrics. This implies that they are able to enjoy balanced energy consumption and balanced cluster formation. On the other hand, older protocols have inferior or untrustworthy performance. The height disparity of bars is a good pointer of disparities in the plan design strategies. Its importance as far as balanced clustering processes are concerned is discussed. It also gives rise to the tradeoff that exists between adaptability and stability. Unbalanced protocols tend to experience node premature failures. This visualization helps in determining sound and strong routing protocols. Overall, the figure emphasizes the significance of these parameters in WSN performance.

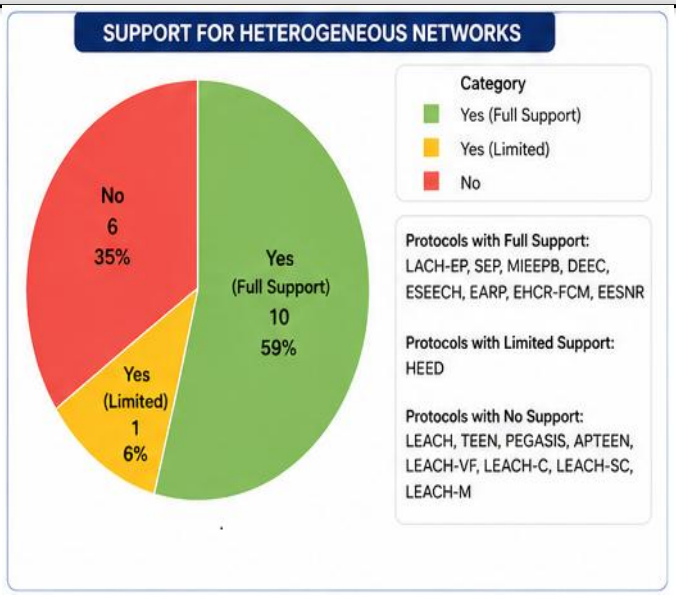

Figure 4

Figure 4 illustrates the distribution of routing protocols based on their support for heterogeneous networks as shown in Table1. The pie chart will categorize protocols into three categories that are full support, limited support and no support. Heterogeneous networks are networks which have sensor nodes of differing energy capacity and capability. The chart indicates that most of the current protocols support heterogeneity completely. This is reflective of the increasing realistic network condition emphasis in recent research. The protocols, such as DEEC, SEP and MIEEPB, are specially designed to cope with heterogeneity of energy. Less comprehensive support is provided by a smaller number of protocols, e.g., HEED. No support is considered to be such procedures like LEACH and PEGASIS. The graph shows the change in the routing protocols over time. It also focuses on the need to accommodate different node characteristics. Provision of heterogeneity results in a better utilization of energy and network life. The diagram gives a clear and concise visualization of protocol capabilities. It helps researchers to choose protocols in the heterogeneous environment. On the whole, such a figure highlights an important element to the contemporary design of WSNs.

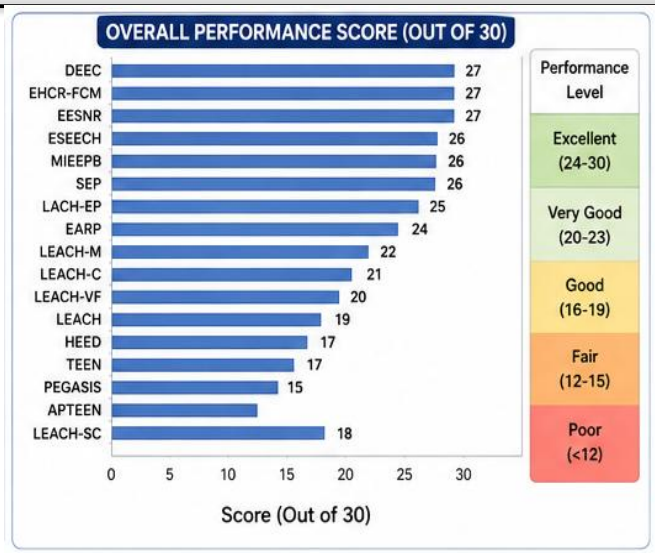

Figure 5

Figure 5 presents a bar chart depicting the overall performance evaluation of the selected routing protocols as shown in Table1. The performance score is obtained by summing up several evaluation parameters. They are efficiency in energy, scalability, load balancing, stability in a cluster and support of heterogeneity. The protocols (DEEC, EHCR-FCM, and EESNR) score the most points, which are above average. These protocols reflect a fair use of energy and optimization of networks. Mid-range protocols have moderate scores, with half-strong parameters. Poorly-ranked protocols are limited in one or more important ways. The chart enables a clear ranking of protocols as a means of easy comparison. It allows fast determining the best routing strategies. The visualization transforms the complex evaluation results into an easily comprehensible format. It also focuses on the development of classical to advanced protocols. The ranking facilitates wise decision making in the choice of protocols. On the whole, the figure is a summarization of the comparative study that is succinct and efficient.

5. Results and Discussion

Infrastructure This has been increasingly added to modern protocols to deal with nodes that have different energy levels, making it necessary in the real-world deployment of WSNs. Conversely, non-heterogeneous-protocols protocols are not as efficient in dynamic networks. As illustrated in Fig. 1, hierarchical routing architectures organize sensor nodes into clusters, where cluster heads perform data aggregation and transmission to the base station. This lowers the overheads in communication and the efficiency of the use of energy. The primary focus of classical protocols, such as LEACH and PEGASIS, however, is on simple clustering and chaining mechanisms which is clearly reflected on the comparative results shown in Table 1. These protocols have some drawbacks in terms of scalability, robustness of clusters and compatibility with heterogeneous environments, which cause irregular energy usage and a short network life.

On the other hand, advanced protocols like SEP and DEEC add in mechanisms which are based on energy awareness and heterogeneity respectively that boost the performance of the network. These protocols are more balanced in terms of various aspects like energy efficiency, load balancing and scalability as observed in the Fig. 2. The probabilistic and residual energy based cluster head

selection method has not only reduced the failure of nodes prematurely, but also achieved a better load distribution. Moreover, the performance comparison shown in the Fig. 3, shows that these protocols can provide better load balancing and cluster stability which are important factors in sustaining a long-term network operation. Advanced routing protocols like EHCR-FCM, MIEEPB and EESNR are utilized for additional performance improvements containing smart clustering and optimisation. They use a multi-hop communication and adaptive decision-making mechanism to improve data transmission efficiency.. The performance scores of the advanced protocols (LEACH, TEEN, PEGASIS, HEED, APTEEN, LEACH-VF, LEACH-C, LEACH-SC, LEACH-M, LACH-EP, SEP, MIEEPB, DEEC, ESEECH, EARP, and EHCR-FCM) are higher than the other protocols because they can balance multiple performance metrics effectively. Moreover, fuzzy logic and optimization techniques can be used to achieve more efficient cluster formation and routing decisions. Heterogeneous network support is also a requirement as indicated in the analysis as shown in Fig.4. Infrastructure This has been increasingly added to modern protocols to deal with nodes that have different energy levels, making it necessary in the real-world deployment of WSNs. On the other hand, non-heterogeneous-protocols protocols are not so effective in dynamic networks. Data aggregation is another critical factor, as it reduces redundant transmissions and minimizes energy consumption across the network.

In general, the results show a clear evolution from simple clustering methods to more sophisticated, adaptive and energy efficient routing methods. Classical protocols are important and baseline models, but modern protocols offer more robust and scalable solutions. But there is no one protocol that is best everywhere, depending on the network and the application. Hence, it is important to choose the right routing protocol for a particular design goal and constraint.

6. Conclusion

This study presented a comprehensive comparative analysis of energy-efficient hierarchical routing protocols in wireless sensor networks. The evaluation was done with respect to the following key performance parameters: energy efficiency, load balancing, data aggregation, scalability, cluster stability, and support for heterogeneous networks. The results show that hierarchical routing is still a good method for improving energy efficiency and increasing network lifetime in WSNs. The most effective protocols of the discussed protocols are the Distributed Energy Efficient Clustering (DEEC) and the Stable Election Protocol (SEP) since they can manage the heterogeneous environment effectively and evenly allocate the energy use. Intelligent clustering and optimization techniques, like Advanced protocols EHCR-FCM and MIEEPB, further enhance the performance of the network. These protocols offer greater cluster stability, scalability and efficiency. However, classical protocols such as Low-Energy Adaptive Clustering Hierarchy (LEACH) continue to play a significant role as foundational models for comparison and benchmarking. Although they are not widely used, they offer good insight into the design of energy efficient routing mechanisms. The research also underscores the need to consider multiple performance parameters to optimize the routing strategy, so as to ensure a balanced and efficient method. In conclusion, the selection of an appropriate routing protocol depends on the specific requirements of the application, including network size, energy constraints, and heterogeneity levels. Future research should focus on the development of adaptive and intelligent routing

protocols that can dynamically respond to changing network conditions. The use of emerging technologies like machine learning and optimization techniques has a great potential to enhance the performance of WSN routing protocols further. This research will serve as a good starting point for researchers to investigate the advanced solutions and research gaps for energy efficient wireless sensor networks.

7. Figures and Tables

Figure 1: Hierarchical Routing in WSN
Figure 2: Overall Comparison (Radar Chart)
Figure 3: Load Balancing & Cluster Stability
Figure 4: Support for Heterogenous Networks
Figure 5: Overall Performance Score
Table 1: Comparison of Energy Efficient Hieratical Routing Protocols

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