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RESEARCH ARTICLE

A Hybrid Multi-Hop Clustering and Energy-Aware Routing Protocol for Efficient Resource Management in Renewable Energy Harvesting Wireless Sensor Networks

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ABSTRACT Energy Harvesting Wireless Sensor Networks (EH-WSNs) main goal is to increase efficiency in settings where Energy Harvesting (EH) is restricted by environmental resources. To solve the drawbacks of conventional Wireless Sensor Networks (WSNs) routing methods that usually ignore EH, this work presents a multi-hop clustering and renewable energy-based routing protocol designed for EH-WSNs. The suggested method performs clustering both centralized and decentralized using energy circumstances and the quantity of captured energy. The protocol operates in three phases: cluster formation, data transmission, and centralized management. To evaluate the effectiveness of the proposed approach, we analyze three distinct scenarios with different settings. The findings show that the suggested approach greatly lowers the total network energy usage while allowing a higher number of nodes to stay operational. We find that our approach outperforms AEHAC, CRBS, HUCL, and EADUC in terms of average energy levels, overall efficiency, network stability, and number of live nodes during the simulation. The results taken together show that the suggested method continuously improves network efficiency and stability in all assessed situations.

INDEX TERMS Wireless sensor networks, clustering protocol, energy harvesting, energy-aware distributed computing.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) comprise multiple sensor nodes spread across different areas, which help monitor the environment by gathering information from them. WSNs, therefore, have wide applicability in several areas, ranging from battlefields polluted areas to buildings, to intelligent highways, to the environment, to healthcare and medicine, etc. [1], [2]. Conventional WSNs rely on non-rechargeable batteries as their source of energy, making the nodes in the network inaccessible when the battery is consumed.

The development of Energy Harvesting (EH) technology in recent years has made it possible to derive energy from various renewable energy resources like solar irradiation,

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mechanical vibrations, and heat through Energy Harvesting Wireless Sensor Networks (EH-WSNs) [3], [4]. Among the numerous benefits that these networks provide over traditional WSNs is that the sensors in them will not fail due to a shortage of energy until the amount of energy they use is less than what they produce [5], [6]. Each EH-WSN node has several components, like the CPU, radio transceiver, side memory, sensors, energy storage unit, and harvested energy unit [7], [8].

While clustering protocols divide the network into clusters, the data is transmitted to Cluster Heads (CHs) by every node. CHs aggregate and integrate the data and transmit it to a sink [9]. While EH can provide a plausible solution to improve the network′s performance [10], clustering protocols can increase its lifetime significantly. EH-WSNs face a unique challenge arising out of EH in the sense that different EH nodes have different energy sources leading to different EH operations.

Though energy can be refilled and stored in a storage unit in a peculiar EH-WSN, it is derived from different renewable energy resources making it dependent on and susceptible to various uncontrollable factors including temperature, solar irradiation, wind, etc.; therefore, it is non-uniform [11], [12], [13]. For instance, a typical solar irradiation-based EH node located in a bright sunny area can harvest more energy as compared to a similar node located in a dark shaded area. Moreover, these nodes cannot harvest energy at night. Therefore, EH nodes should not only be able to receive energy but also be able to store it in the battery for future use. Second, the capacity of the rechargeable battery is limited. These unique properties of EH-WSN which result in the inefficiency of the proposed routing protocols of WSNs in EH-WSN, must therefore be considered while designing a routing algorithm [12], [14]. Thus, the objective of routing design in EH-WSNs is to optimize the operational efficiency of the network by maximizing the power generated through it subject to EH constraints using hierarchical clustering which can significantly improve the performance of the network [6], [12].

The difference between an EH-WSNs node and a battery-powered sensor node is that, in a battery-powered sensor node, the total energy is reduced over time and a sensor node can work until the energy level reaches an unusable level [15]. But in the EH sensor node, in case of insufficient harvested energy for sensor node powering, the node goes into sleep mode for recharging. Therefore, the energy is both researchable and reusable [16], [17]. Due to the unique characteristics of EH-WSNs, existing WSN routing protocols aren′t suitable for these networks [15], [18].

There are various energy sources for EH sensor nodes [17]. Generally, harvesting energy in WSN is divided into three categories of radiant energy: sunlight, thermal energy, and mechanical energy (such as vibration, wind, etc.) [17].

Moreover, an EH-WSN node is made up of several components. Typically, an EH sensor node includes a sensor unit, a communication unit, an EH unit, an energy storing unit, a processing unit, a positioning system unit, if necessary, and a motion unit [17], [19], [20]. Figure 1 shows the structure of an EH sensor node.

The paper′s contributions are:

1. Simultaneous operation (i.e., CH selection is not required in each round)

2. Employing a strategy is essential for improving the accuracy of selecting the CH in a large-scale network. However, if the network is not large-scale, the usage of node messages may be avoided to decrease network overhead.

Direct practical uses for this approach abound in real-world situations including crisis management, smart farming, and environmental monitoring. Using EH-WSNs with solar energy collecting in remote agricultural fields, for example, can help to continuously monitor soil moisture, temperature, and other parameters without depending on battery replacement or outside power sources. Our approach guarantees continuous data transmission and extended network lifetime even in changing energy conditions by dynamically modifying the clustering of nodes depending on their energy status and harvesting capability.

The approach used in this paper is one of the inequitable strategies that relies on layering. The nodes in the first layer will possess a reduced radius, whereas the nodes in subsequent levels will have an augmented radius.

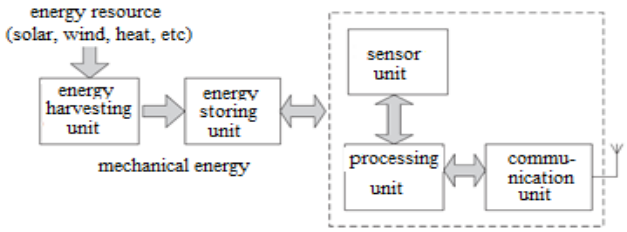


FIGURE 1. The structure of an EH sensor node [15].

To be up-to-date and due to the extensive applications of EH-WSN, in this study, we try to provide a complete definition of this type of network, its main components, and a summary of research done on this field. Accordingly, hierarchical routing protocols in WSNs and EH-WSN are investigated in Section II. The proposed method is provided in Section III. The proposed method is compared to other methods in Section V and Section IV concludes the paper and introduces some recommendations for future works.

II. RELATED WORK

Hierarchical methods are efficient methods that can improve network efficiency. In this section, we first investigate clustering protocols in WSNs and then protocols in EHWSNs.

In recent years, many routing protocols have been proposed for WSNs.

We begin with an understanding of the solar-aware Low Energy Adaptive Clustering Hierarchy (S_LEACH) [21] protocol in which nodes transmit data to CHs. The CHs collect data from the source, compress it, and send it to the sink

where it will be processed. Solar nodes have an increased chance of becoming CHs in this procedure, whereby each node employs a stochastic method in each round to decide if it will become a CH in that round. The centralized nature of this approach, however, makes it inappropriate for high-dimensional networks.

Among the disadvantages of this method, it can be pointed out that the authors could use an optimal algorithm to select the CH in order to choose the CH correctly.

Another hierarchical routing strategy for EH-WSNs is described in [18], which operates under the premise that no battery is required for any of the sensors. In Adaptive Energy-Harvesting Aware Clustering (AEHAC), nodes that can harvest energy at a higher speed as compared to others have a higher chance of becoming CH. Though each node can evaluate its harvesting speed in a short time through this method, it does not consider the density of nodes (the number of neighbors of a node) or their distance from the sink.

One of them is the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol [22] proposed in 2002, which distributes clusters randomly. According to a predefined probability, each node can be the CH and this role circulates among different nodes until finishing its battery. Other nodes connect to CH with the minimum energy needed to connect.

Another useful algorithm is the Hybrid Energy-Efficient Distributed Clustering (HEED) [23] which was proposed in 2004. In this paper, CH uses the multi-hop method for transmitting data to the Base Station (BS), which leads to improved energy consumption.

Energy Potential Low Energy Adaptive Clustering Hierarchy (EP-LEACH) [24] protocol proposes an energy potential function to measure the EH potential of a node. For this procedure, CHs with greater energy levels have a better probability of being selected. More importantly, a node may become a CH as many times as possible. This is a distributed method wherein the main purpose is to assign tasks to nodes with higher energy potential. Like AEHAC, this method also does not consider the distance from the sink and network density (number of neighbors of a node in a network).

Maximum Energy Grage Algorithm (MEGA) [25] is an energy-oriented dynamic algorithm that reduces network overhead unlike time-oriented algorithms like LEACH that reduce time. This paper proposes a self-powered WSN protocol that harvests energy from mechanical vibration in the environment and illustrates its efficiency by applying it to a smart bridge through simulation. This method of EH through vibration can be further developed taking other sources of renewable energy into consideration.

Among the disadvantages of this method, we can point out that this paper will only consider the main functions of the network and a simple EH scenario.

Energy Neutral Clustering (ENC) [16] is a clustering protocol based on the principle of WSNs. Cluster Head Group (CHG) is an ENC technique that enables a cluster to utilize several CHs to distribute the burden of high-volume traffic and to cut down on control message overhead. However, in this method, CH nodes are restrained to sense the environment. In addition, many of these nodes are not used during other nodes' turn which reduces network efficiency as compared to a permanent network.

For each node that is a CH or a member of the cluster, the Clustering Routing Algorithm Based on Solar Energy Harvesting (CRBS) [26] provides a threshold-sensitive resurrection mechanism. The CRBS algorithm proposes a threshold-sensitive resurrection method, resurrecting the node when the soft or hard EH threshold is reached. Using this strategy in conjunction with the current degree of EH, the CH node may determine whether or not to reappoint the CH for the subsequent cycle. CRBS improves the CH election threshold to restrict the incompetent node in the election. This protocol sends data effectively at the expense of preventing a node from completing more operations for more charge and with less regard for balanced energy usage, CH position, and distance to the sink.

Among the disadvantages of this method, he pointed out that the proposed method could not work well in the way of data transmission and increased the amount of energy consumption in the network. Therefore, the lifetime of the network was reduced.

The Clustering Routing Algorithm (CREW) is introduced in [27] for address the issue of unstable and imbalanced energy distribution among sensor nodes in EH-WSNs. The suggested technique consists of two distinct stages: cluster creation and data transmission. The first stage of the process involves using the network gradient and waiting time for CH competition to divide the network into clusters of varying sizes. CHs are then selected based on the residual energy and energy gain of the nodes. During the second phase, a dynamic inter-cluster communication system is deployed to efficiently store and use the collected energy.

The presented method does not have information about nodes′ traffic, neighboring nodes′ energy and local distance to select the optimal CH, so it cannot choose the optimal CH in each round and ultimately the network′s lifetime will decrease.

A technique for energy-aware distributed clustering routing in EH-WSNs was presented in [28]. This technique incorporates the node′s present residual energy and collected energy in a short-term prediction horizon into the distributed clustering routing CHs election process. To make the protocol energy-aware, a neural network-based solar energy prediction model was investigated. In this approach, the chance that a node is a CH is increased for nodes with more residual energy and enhanced energy-collecting capabilities. The suggested routing technique was compared against LEACH in terms of network performance and number of awake nodes. Simulation findings show that the suggested clustering routing has a greater capacity to balance energy consumption across sensor nodes and boosts network speed by about 30% compared to LEACH. However, this method does not consider node location for determining suitable CHs.

Jin et al. [29] solved the problem of target coverage in WSN and EH using integer linear programming considering the space between the energy distribution and sensor nodes. In order to overcome the aforementioned issue, they suggested two algorithms: the Local Greedy Threshold Algorithm based on Confident Information Coverage (LGTA-CIC) and the second one was Overall Greedy Search Algorithm based on CIC (OGSA-CIC). The authors compared their approach to others to illustrate how effective it is and how the suggested algorithms might lead to better results at reduced cost. The presented method does not have information about the traffic of nodes.

Wang et al. [30] used Energy-Harvesting Relays (EHRs) to increase the durability of WSNs. They proposed an approximate algorithm called the effective relay deployment algorithm to cover the entire network with minimum relays. There are two phases in the presented algorithm disk cover and connector insertion. The suggested technique was shown to be 45% more efficient in decreasing the number of EHRs in the network in simulations.

In [31], the Deep Learning (DL) method has been applied in EH-WSN to solve the problem of energy prediction in a receiver node. The authors have shown the effectiveness of the suggested strategy via simulations using actual data, demonstrating that it reduces both data packets and transmission latency.

Tukisi et al. [32] have developed a Particle Swarm Optimization (PSO)-based routing system for EH using three energy-efficient routing techniques of WSN. The first strategy is designed to maximize the energy of the node in the WSN that has the lowest energy (the node with the worst performance), the second strategy is designed to maximize the energy of the entire WSN, and the third strategy is designed to maximize the energy of the node with the worst performance while simultaneously improving network latency. The most promising of these solutions underwent further testing in a WSN that included nodes for EH. When compared to the LEACH method, the results of the simulation demonstrated that the PSO algorithm produces a greater rise in network energy and a greater improvement in network lifetime.

One drawback of this strategy is that the suggested algorithm does not take into account aspects such as connection quality, route cost, traffic aggregation by CH, network coverage, and network convergence rate.

Puviaraus et al. [33] have designed a protocol named Dynamic Uneven Clustering Protocol (DUCP) in order to optimize the energy consumed by sensory components in EH-WSNs. To reach this aim, the protocol clusters harvested energy sources and chose the best nodes as CH. To overcome the capacity limitation, a power management strategy was also provided that manages the energy consumption of cluster members and CHs as well. However, this method does not consider node location for determining suitable CHs.

Hmidi et al. [34] combined the two aspects of EH and mobility in a new framework, Mobility and EH aware Medium Access Control (MEH-MAC), to increase the performance of dynamic sensor networks. The network was supplied by ambient energy and contains both static and mobile nodes. To overcome the energy limitation of mobile nodes, mobility was utilized to produce energy.

Since there is a direct connection between communication protocol and network performance, Luo et al. [35] studied the problem of inter-communication strategy in fixed clustering methods. They provided method which uses a random relay strategy to improve this kind of communication which in turn optimizes the network configuration required for harvesting capability and finally the cost of network deployment. As fixed clustering protocols aren′t so reliable due to using different software and hardware, the authors used the same kind of software and hardware capabilities to increase this feature of their protocol. However, this protocol does not consider node location for determining suitable CHs.

Miao et al. [36] proposed a method for energy utilization in oil and gas Internet of Things (IoT) [37]. In this solution, nodes are assigned tasks according to their energy level, and clusters are also selected in accordance with the ratios of EH to energy consumption. The aims of this solution were saving energy and extending lifetime and also reducing the delay in transmitting important data.

Abdul-Qawy et al. [38] proposed a multilevel heterogeneous reactive protocol named Threshold Enabled Scalable and Energy Efficient Scheme (TESEES) which can support different kinds of nodes. The aim of providing this method was to optimize energy consumption in large IoT-based WSNs. In this strategy, nodes wait in energy-saving mode until a new value arises to be sent. This way, energy is saved to a great extent and as a result, network lifetime is also increased.

One of the disadvantages of this method is that it does not consider different network settings, including small, medium, and large-scale deployments. Also, the energy consumption of the entire network has not been saved.

Being supplied by battery is a big limitation for node performance in WSNs. The network will die as soon as batteries are completely used, which in turn reduces the network lifetime. To overcome this challenge, the Golden Eagle Optimization Algorithm (GEOA) and an upgraded version of the grasshopper optimization algorithm were suggested by Roberts and Ramasamy [39] with the purpose of reducing energy consumption and, as a consequence, extending the product′s lifespan. This method was able to select a reliable route between CH and BS according to some parameters including node degree. However, this method does not consider node location for determining suitable CHs.

Liu et al. [40] addressed unbalanced energy consumption among nodes which can result in node dying and therefore network loss. An adaptive routing strategy for WSNs that is also capable of EH was proposed by the authors as a way to address both this shortcoming and its repercussions it. In order to optimize energy consumption, at each data

transmission hop, the optimal mode is chosen so as to balance energy among nodes and finally reduce energy waste and increase network lifetime. One of the disadvantages of this method is that it does not consider different heterogeneous networks.

A novel adaptive coding routing protocol that is incorporated in cluster-based routing protocols was presented by Doanoune et al. [41] in order to increase energy efficiency and network dependability. The selection of CH was determined by the amount of energy that was left in the nodes, and an equal clustering technique was used so that there would be no imbalance in the energy. Similar throughput was achieved by the suggested methodology as compared to LEACH and Balanced Residual Energy-LEACH (BRE-LEACH). However, this method does not consider node location for determining suitable CHs.

Prakash and Pandey [42] studied CH selection and suggested the combination of a new Energy-Efficient Clustering Strategy and PSO named (PSO-EECS). The purpose was to maximize the lifespan of the network while simultaneously reducing the amount of energy that was wasted. The approach was able to accomplish the desired level of network stability and operation duration, in addition to optimizing fitness characteristics such as energy, load balancing, distance, node density, and the network′s average energy. Because of the importance of EH mechanisms on WSN′s lifetime, this subject has been studied by many researchers. An important aspect of EH-WSNs is the relationship between EH techniques and Medium Access Control (MAC) protocols.

In this regard, Sherazi et al. [43] reviewed EH methods proposed so far for WSNs and their MAC protocol advantages and disadvantages for EH-WSNs with special attention to underlying techniques, performance criteria, and evaluation procedures.

Due to the importance of EH in prolonging network lifetime and availability of Radio Frequency (RF) energy for this purpose, Singh et al. [44] decided to propose a new scheme to implement RF-energy transmitters in IoT networks by taking into account data routing information, energy-hole information, and node-connectivity information, as performance parameters. In addition, in order to prevent RF-wave propagation damping and improve the accuracy of wave modeling, in addition to, the approach for the robust hybrid propagation of RF waves was presented. The method was able to address energy holes and extend the network lifetime. Among the disadvantages of this method, it can be pointed out that the path of the sink is not optimal for collecting data and EH in the network.

Efficiency in the use of energy is the primary obstacle that must be overcome in WSNs, and several approaches have been proposed as potential solutions. Among them, EH has been provided as a solution for battery recharge in order to address the energy limitation of sensor nodes. inspired by this strategy and adopting the hierarchical clustering routing method, Sah and Amgoth [45] proposed a Novel Energy Harvesting Clustering Protocol (NEHCP) which has three phases: initial stage, set up, and data transmission. As previously investigated references, the outcome of this method was energy saving and so network lifetime proliferating.

Bahbahani and Alsusa [5] proposed a new version of the so-called routing algorithm, LEACH, suitable for EH-WSNs. In this new version, the CH role is shared among nodes to balance energy consumption. During non-CH, nodes perform data transmission to maintain energy. The authors demonstrated that their scheme was especially suitable for highly constrained energy environments.

Li et al. [46] proposed a prediction algorithm to improve network performance by considering EH constraints. In order to accomplish this goal, the authors devised a new clustering protocol that they called the Energy and Density Adaptive Clustering protocol, or Energy and Density Adaptive Clustering (EDAC) for short. The goal of this protocol was to boost the network throughput and transmission ratio of EH-WSNs.

In 2015, the Hybrid Unequal Clustering with Layering Protocol (HUCL) protocol [47] was proposed as a hybrid unequal clustering algorithm for increasing the network lifetime. This paper improves the HUCL protocol [47] and Energy Aware Distributed Unequal Clustering Protocol (EADUC) [48], In this method, clusters with unequal sizes are created. Clusters close to the BS are smaller. For determining the competition radius of cluster nodes, other parameters such as energy are also considered. In this method, the energy of each node in selecting the next step is considered for intra-cluster routing.

Next paper investigates a protocol with high efficiency aiming to achieve a high transmission reliability and energy gain called Network Coding based Cluster-level Multipath protocol in Duty-Cycles (NCCM-DC) [49]. In this protocol, nodes are organized in a cluster and cluster is used as a basic unit for building multiple paths. In this method, traffic load can be distributed among more nodes. However, using route redundancy, transmission reliability is increased. This method focuses on dormancy mechanism and collaborative state transmission algorithm which reduces energy consumption.

In 2017, Optimal Clustering in Circular Networks (OCCN) was proposed to increase the lifetime of the network [50]. In this method, optimal parameters including single step optimal communication, optimal number of clusters, optimal number of nodes of a cluster for a circular network is considered, this protocol presents a distributed reservation-based CH selection mechanism for reducing overhead of the network.

In 2017, Energy efficient clustering protocol based on improved metaheuristic was proposed [51]. This paper employs an improved Artificial Bee Colony (ABC) algorithm for routing in which optimal CHs are selected based on a fitness function and energy utilization in a WSN is improved. Simulation results show that the proposed clustering protocol has better performance in terms of packet delivery,

generation capacity, energy consumption, network lifetime, and delay.

S-LEACH [21] is one of the clustering methods for S-LEACH which was proposed in 2004, and it is an extension of the LEACH protocol. In this protocol, CHs are selected directly by the BS, and in the next rounds, new CHs are determined by the current CHs. This protocol uses solar energy as an energy resource.

Advanced Solar-aware Low Energy Adaptive Clustering Hierarchy (A-sLEACH) [52], as an improvement to the S-LEACH protocol, was proposed in 2007. The CH is selected by the BS using a scanning method and taking into account the cluster nodes as points of the convex body (shell). In the next rounds, the current CH selects a node powered by solar energy as the new CH using the previous strategy.

The other protocol is the category of clustering algorithms for maximizing WSNs' lifetime with EH sensors [53] which uses only solar EH nodes for relaying and routing and thereby increases the lifetime of the network.

Another paper is Secure Routing Protocol using Cross-Layer Design (SRPCLD) which was proposed in 2013 [54]. In this method, clustering is performed in a distributed manner such that neighboring nodes are connected to each other in two steps. In cross-layer design, parameters are exchanged between different layers such that energy is employed effectively and optimally. Compared to other clustering protocols, this method performs better in terms of network lifetime, number of alive modes and residual energy.

Discrete Particle Swarm Optimization (DPSO) clustering routing algorithm [55] is a centralized routing protocol. At the beginning of each round, the BS checks the status of all nodes and executes the DPSO algorithm after creating initial population.

The study conducted by Khernane et al. [56] compiles and examines several sources of EH for WSN applications in the sector of agriculture. The process of constructing this compilation required significant time and effort. They conducted extensive study on several topics like energy harvesting, precision agriculture, and renewable energies to compile this article. It serves as a valuable source of data for scholars in these subjects as well as other related disciplines.

A novel relay selection technique is suggested in [57] to optimize energy consumption, enhance network performance, and extend the lifespan of communication networks in energy collecting WSNs. The suggested technique involves a mathematical analysis of the energy consumption and solar energy status of sensor nodes. Next, the cooperation probability is maximized by imposing a limitation on the interruption probability threshold. This constraint allows for control over the participation of relay nodes in cooperative transmission, hence conserving energy in the system. The most appropriate node is selected using a multi-criteria relay selection method depending on the solar energy status, network energy balance, signal-to-noise ratio, and relay node outage probability.

Azarhava et al. [58] examine a EH-WSN that utilizes Non-Orthogonal Multiple Access (NOMA) for communication. In this network, all sensors obtain their energy from a Hybrid Access Point (HAP) and, if they have sufficient harvested energy and data to transmit, they simultaneously send their information to the HAP using the NOMA-based protocol. The resource allocation is formulated as an optimization problem with the objective of maximizing energy efficiency. Energy efficiency is defined as the system throughput divided by the total energy consumption in the network, which is the sum of energy consumption in the downlink and uplink phases.

In [59] presents a multi-hop clustering routing protocol called simultaneous wireless information and power transfer (SWIPT)- and imperfect spectrum sensing-based multi-hop clustering routing protocol (ES-ISSMCRP) for energy harvesting-cognitive radio sensor networks (EH-CRSNs), which is based on SWIPT. The ES-ISSMCRP protocol efficiently utilizes downlink RF EH and SWIPT technologies to optimize and distribute the remaining energy across nodes, significantly extending the network′s lifetime while preserving its surveillance capabilities. However, in the ES-ISSMCRP protocol, EH-CRSNs nodes only collect energy via direct connections with the sink. The significant loss in signal strength decreases the efficacy of energy harvesting for nodes that are far away from the sink. This limitation hampers the potential of EH technology to prolong the lifetime of the whole network.

A multi-hop uneven clustering routing algorithm is presented in [60] for EH-CRSNs that use simultaneous wireless information and power transfer (SWIPT) technology. More precisely, a state function based on EH is suggested to precisely monitor the fluctuating energy levels in nodes. This function incorporates dynamic spectrum availability, neighbor count, and other data to provide the criteria for picking high-quality CHs and relays. This, in turn, enables efficient data transmission to the sink. SWIPT methods are used inside clusters and between clusters to provide quick energy replenishment for CHs or relays that have insufficient energy during data transmission. This prevents data transmission failures caused by energy depletion. A system for energy status management is implemented to prevent energy waste resulting from excessive activation of the SWIPT mechanism.

Benelhouri et al. [61] have suggested an enhancement to the homogeneous Gateway-Based Energy-Aware Multi-Hop Routing (MGEAR) protocol in order to extend the lifespan of the network and increase the data transfer rate of heterogeneous wireless sensor networks. The Heterogeneous Multi-hop Energy-Aware Routing (HMGEAR) network concept utilizes two forms of data transfer: direct transmission and multi-hop transmission. This technique allows for the equitable distribution of energy depletion across all sensor nodes based on their starting energy levels and distances from the BS. In order to avoid exhausting the energy of nodes due to long-distance transmission, a gateway is strategically

positioned in the middle of the monitored area. Its primary function is to collect and consolidate data from the sensors, and then distribute it to the BS.

A novel clustering technique for WSNs was introduced in [62]. The protocol aims to address the problem of hotspot formation, optimize energy consumption, and provide a balanced distribution of energy across all network nodes. The Energy-efficient Multi-hop routing with Unequal Clustering approach (EMUC) protocol is a distributed method that is energy-efficient and utilizes an uneven clustering routing system. It is specifically designed for usage in wireless sensor networks that include periodic data gathering. The technique under consideration partitions the network into many clusters, each characterized by varying cluster sizes. The clusters in closer proximity to the BS have lower sizes, whereas those located farther away show greater sizes. The nodes engage in competition to become CHs using a probabilistic model and taking into account the remaining energy of the nodes. The minimal transmission energy method is used to compute the most concise route between the CH and its member nodes. In this section, some clustering protocols introduced for increasing lifetime of WSN and efficiency in EH-WSN are investigated. Considering unique characteristics of EH-WSN, clustering protocols proposed in WSN are not efficient. On the other hand, despite proposing such clustering protocols for EH-WSN, efficiency enhancement in constrained EH condition is still a problem. The primary objective of the proposed technique is to provide a clustering protocol that achieves high accuracy and little overhead, hence enhancing network efficiency and surpassing current methods. In the proposed method, an unequal clustering is proposed. The BS determines strategy performs clustering according to the location of nodes. Clustering is performed in a distributed manner based on harvested energy. Inter-cluster and intra-cluster routing are performed based on layering. Moreover, a new mechanism is proposed through introducing CH group including CH and assistant CH for transmitting data in the cluster. In this approach, new Cluster Heads are chosen only if the energy level of the existing CHs falls below the specified threshold value. In the following, we will examine the suggested approach.

In this section, some clustering protocols introduced for increasing lifetime of WSN and efficiency in EH-WSN are investigated. Considering unique characteristics of EH-WSN, clustering protocols proposed in WSN are not efficient. On the other hand, despite proposing such clustering protocols for EH-WSN, efficiency enhancement in constrained EH condition is still a problem. In the proposed method, the main purpose is to propose a clustering protocol with high accuracy and minimum overhead which increases the efficiency of the network and improves existing methods. In the proposed method, an unequal clustering is proposed. The BS determines strategy performs clustering according to the location of nodes. Clustering is performed in a distributed manner based on harvested energy. Inter-cluster and intra-cluster routing are performed based on layering. Moreover, a new mechanism is proposed through introducing CH group including CH and assistant CH for transmitting data in the cluster. In this method, new CHs are selected only when the energy of current CHs is lower than the threshold value. In the following, the proposed method is investigated.

III. THE PROPOSED ALGORITHM

This section presents a very effective hierarchical routing technique designed specifically for EH-WSNs. Initially, we provide the network model and issue formulation, followed by an explanation of the suggested method.

A. NETWORK MODEL

Imagine a WSNs that has EH devices and a BS with an inexhaustible power source linked to the network. The data is collected by sensor nodes located at a distance and then sent towards the BS. Every node has the potential to function as either a CH or a cluster member. The assumptions of the network model are explicitly specified as follows:

- There are N energy harvesting sensor nodes distributed randomly in an $M \times M$ area,
- Nodes are homogeneous,
- All nodes and BSs are fixed,
- All nodes have the ability to adapt their transmission power based on the distance,
- CH can aggregate and integrate data,
- The energy consumption model of the radio is identical to that of the LEACH protocol [22].

Since environmental energy is available and varies over time, we assume that an EH node has a unique EH rate. The EH is stored in a storage device (like a battery).

In this paper, a prediction model [55], [63] is used to model the EH. The accessibility of the wireless node′s energy according to the model [63] is depicted in Figure 1. Figure 2 shows how energy is accessed by nodes.

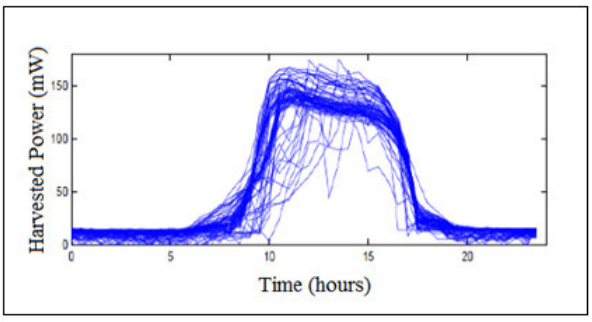


FIGURE 2. Solar power harvesting rates of a sensor [63].

A simplified model [63] of the model proposed in [55] is used for modeling energy harvest. Figure 3 shows EH model based on solar radiation.

EH of node i is obtained from Equation (1).

$$E_{rem}(i, r) = (min(E_{Max}(i), E_{rem}(i, r-1) + E_{EH}(i, r-1)) \quad (1)$$

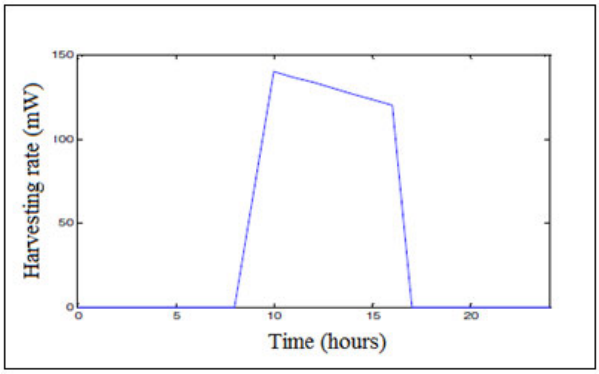


FIGURE 3. EH model of sensor nodes [55].

where $E_{rem}(i, r)$ is the amount of energy of node i in repetition round r, which shows the energy consumed in node i in the previous round and the maximum battery capacity of node i. The amount of energy consumed by node i is obtained from Equations (2) and (3).

$$E_{EH}(i, r-1) = \mu_i \Delta t \tag{2}$$

$$\mu_i = rand(P_{h,Min}(r-1), P_{h,Max}(r-1)) \tag{3}$$

where, μ_i is the amount of energy consumed by node i at round $r-1$. $P_{h,Min}(r-1)$ and $P_{h,Max}(r-1)$ indicate the maximum and minimum energy consumption in all nodes respectively. Δt is the finish time of a round. This equation is used to model the variability in energy consumption by different nodes in the network, reflecting real-world scenarios where energy consumption can fluctuate due to various factors.

B. HANDLING STAGE

The proposed EH-WSN method is implemented in three stages: 1) The handling stage which is centralized, 2) Cluster initialization, and 3) Data transmission which is distributed. BS is responsible for layer construction, radius calculation, and node degree determination. Then the protocol works in a distributed manner in step 2: Cluster Initialization and Data Transmission stage.

The suggested technique assumes that all nodes possess prior knowledge of their position information, which is derived from frequency power. This approach involves selecting a node with more energy than the rest as the CH.

In this method, the Cluster Initialization step is only performed when the energy status of the current CHs is below the threshold energy $E_{th} = E_{avg} - E_{std}$. This threshold is adopted from [63]. Here, E_{avg} represents the average energy of alive nodes, and E_{std} is the standard deviation of the residual energy of all alive nodes. This approach reduces overhead and energy consumption associated with transmitting control packets and decreases computation time in the network. Figure 4 illustrates the flowchart of EH-WSN called MHCRP.

Initially, after deploying nodes in the network environment, the BS transmits a message across the network. All nodes then calculate their distance to the BS based on signal strength. Subsequently, nodes are layered according to their distance from the BS, with layering achieved through multiple hops. It is important to note that clustering is distinct from layering.

In this layering manner, nodes that are located at a distance less than d_0 to the BS are excluded from layer formation and are located in the first layer by default. In addition, the BS calculates the neighborhood radius of each node and the overall strategy of the network as well. To do these, the BS calculates the distance between the farthest and nearest nodes to itself as Equation (4):

$$d_N = d_{max} - d_{min} \tag{4}$$

In this equation, d_N represents the difference between the distances of the farthest and nearest nodes to the BS. Here, d_{max} is the distance from the farthest node to the BS, and d_{min} is the distance from the nearest node to the BS.

Complete linkage (or farthest point linkage) was used to determine the distance between clusters. In this method, the distance between two clusters is defined as the maximum distance between any pair of points, one from each cluster. This method ensures that all points within a cluster are relatively close to each other, providing more compact clusters and helping to minimize the maximum intra-cluster distance.

We have established four levels for the transmission of data from CHs to the BS. The length of each layer is determined using Equation (5):

$$L_{RL} = \frac{d_N}{4} \tag{5}$$

where L_{RL} is a limitation on layer length and d_N represents the difference between the distances of the farthest and nearest nodes to the BS.

In order to determine the network strategy; if L_{RL} is less than the threshold (Rl_{Max}, the maximum radius of a node in layer 1), the BS broadcasts the first strategy. According to the second strategy of clustering, if nodes are close to each other, due to the short transitional distances, local information of neighbors isn′t needed for CH selection. In fact, there is no force on nodes to broadcast their local information in the network which causes to impose overhead on the network. In MHCRP, the primary parameters for clustering are the amount of harvested energy and the current energy level of the nodes. When L_{RL} exceeds the threshold, indicating longer transmission distances, the BS selects the first strategy. In this strategy, nodes require neighbors′ information for clustering, so each node must broadcast its local information, increasing overhead but enhancing clustering accuracy and network efficiency.

This overhead leads to careful clustering and increases network efficiency. The second operation of the BS is calculating cluster radius for each node, which is obtained using Equation (6):

$$R_c(i) = \left[1 - \alpha\left(\frac{dBS_{BS,max}}{dBS, min_{BS,max}}\right) - \beta\left(1 - \frac{E_{rem}(i,r)}{E_{Max}}\right)[]_{max} \right] \tag{6}$$

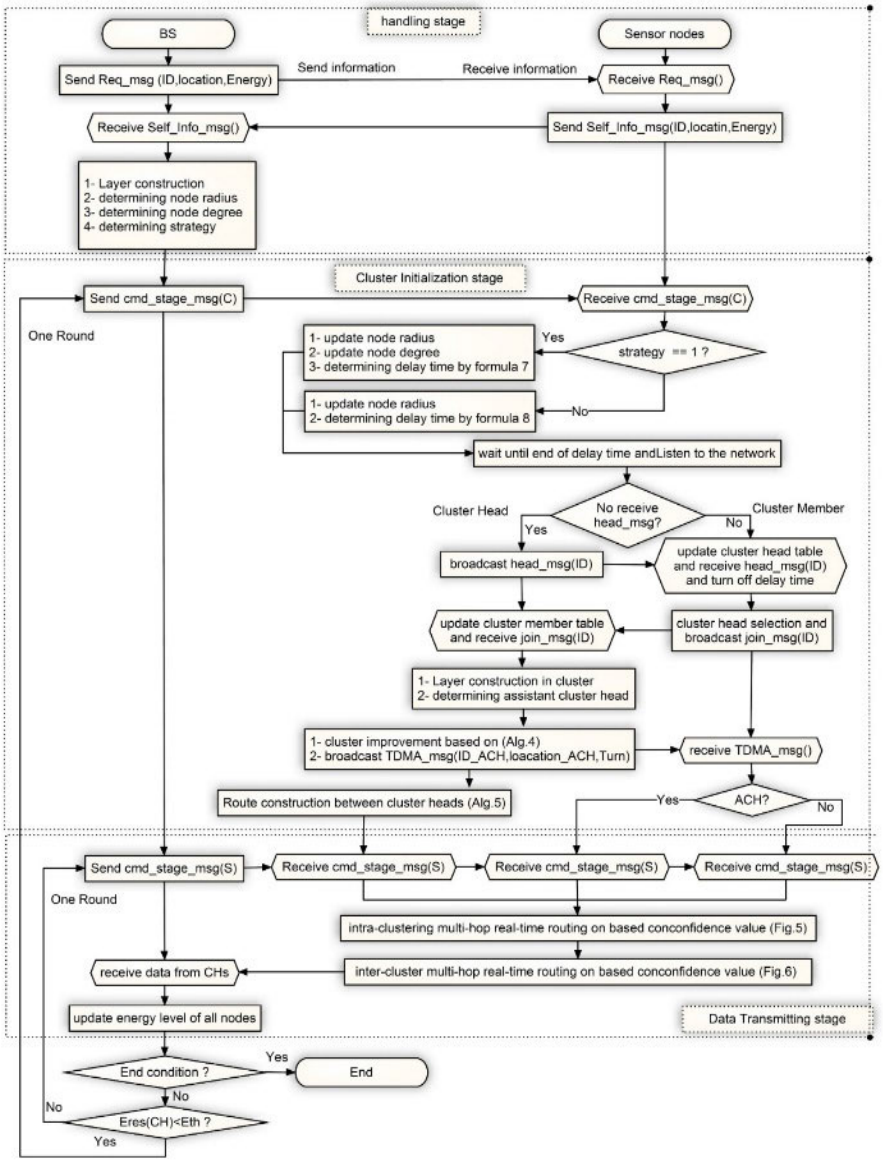


FIGURE 4. Flowchart of the proposed EH-WSN called MHCRP.

where, $R_c(i)$ indicates the radius of node i and RL_{max} is the maximum radius. α and β are weight coefficients in range [0, 1]. $E_{rem}(i, r)$ and E_{max} represent the amount of energy remaining in node i at round r and the maximum energy of a node, respectively. Finally, $d_{BS,max}$ and $d_{BS,min}$ indicate the maximum and minimum distance from node i to BS and $d_{BS}(i)$ is the distance from node i to BS.

C. CLUSTERING STEP

At this step, network nodes are divided into k clusters. Network initialization includes five phases: 1) Delay calculation phase, 2) CH selection phase, 3) Cluster formation phase, 4) Cluster improvement phase 5) Route construction.

During the first phase, nodes determine the amount of time it takes for them to become CH by calculating their delay time. Once the BS announces the initial strategy for nodes, each node adjusts its radius based on Equation (6). Subsequently, each node exchanges its energy level with neighboring nodes prior to computing the delay time. After nodes determine their neighboring nodes and update their degree, which represents the number of neighbors, they proceed to compute their delay time. The delay time in the first approach is calculated using Equation (7).

$$T_w(i,r) = \frac{E_{Max}(i)}{E_{rem}(i,r)} \times \frac{1}{max(E_{EH}(i,r),\varepsilon)} \times \frac{1}{|NL(i,r)|} \times \sum_{j \in NL} \frac{max(\frac{E_{rem}(j,r)}{E_{Max}(j)},\varepsilon)}{1-\frac{d_{i,j}}{R_c(i)}} \times max(\alpha(i),\varepsilon) \times d_{BS}(i) \times V_r \times T_2 \quad (7)$$

where, T_w is the time latency of node i, and ε is a small number that, if equal to zero, would have no effect on the

equation. T_2 indicates the time spent for phase 2 and V_r is a random number in [0.1, 0.2]. In addition, if the second strategy is selected and nodes don't require knowing about their neighbor's status, the delay time of each node is obtained according to the simplified version of the previous Equation (8):

$$T_w(i,r) = \frac{E_{Max}(i)}{E_{rem}(i,r)} \times \frac{1}{max(E_{EH}(i,r),\varepsilon)} \times \frac{1}{max(|NL(i,0)|,\varepsilon)} \times d_{i,BS} \times max(\alpha(i),\varepsilon) \times V_r \times T_2 \quad (8)$$

where, $|NL(i,0)|$ indicates the number of neighbors assigned to node i by BS. Algorithm 1 shows the delay calculation phase in the cluster initialization stage in MHCRP.

Algorithm 1 Delay Calculation Phase in the Cluster Initialization Stage in MHCRP

```
begin
    S[i] state node;
        while (CT < T2)
            Vr = rand(0.1, 0.2);
                if strategy = 2
                    Broadcast Neighbor_Msg;
                        while (CT < Tb)
                            Receive Neighbor_Msg;
                              update neighbor List NL [ ];
                         end while
                            Calculate Tw by Equations (3-9);
                    else if strategy = 1
                        Calculate Tw by Equations (3-10);
                end if
            end while
        t = T1 + Tw;
end
```

During the second phase, every node remains idle until its latency period concludes. If a node does not receive the CH message from its neighbor during the latency period, it will subsequently transmit the CH message to the whole network after the latency period has ended.

Algorithm 2 CH Selection Phase in the Cluster Initialization Stage in MHCRP

```
begin
    while (CT < T2)
        if (CT > T)
                state = CH;
                Calculate Rc;
                broadcast Head_Msg;
                receive Head_Msg from competition CH;
                store in Head_List HL[] along with distance;
            else if (received Head_Msg from any neighbor);
                    state = CM;
                  store 'si' in Head_List HL[] along with distance;
            end if
        end while
end
```

In the third phase, after CH selection, clusters are formed and then CHs broadcast a message to announce that they are CH. After that, the non-cluster nodes will join a CH with the least energy needed for transmitting data. Similarly, these nodes send a message to their CH in order to announce their joining. This message includes their energy level. At this step, each CH conducts intra-clustering layering and then estimates the average distance between nodes and itself.

Nodes with less distance than average are located in the first layer and nodes with more distance than average are located in the second layer. Then CH selects nodes having energy more than the average energy of nodes of the cluster and locates them in the first layer as an assistance for CH. If one node is in the second layer, the nearest node is selected among CH and assistance to CH and transmits packets to this node. Algorithm 3 shows cluster formation phase in the cluster initialization stage in MHCRP.

Algorithm 3 Cluster Formation Phase in the Cluster Initialization Stage in MHCRP

```
begin
  while (CT < TimePh3)
    while (CT < TimeBrc Ph3 for Join-msg)
      if Sensor[i].state = Cluster Member
        select the nearest ClusterHead Sensor[j] from
    ClusterHeadL[] list;
        Sensor[i]. head = Sensor[j];
        send JoinClusterMsg to Sensor[j];
        else if Sensor[i].state = ClusterHead;
            Receive JoinClusterMsg from ClusterMember;
          store in ClusterMember[] List;
        end if
    end while
        if Sensor[i].state = ClusterHead
            Sensor[i].state = ClusterHeadP;
            Calculate Layer in Cluster & Assists CHnode;
      end if
  end while
end
```

In the fourth phase, after cluster formation, cluster optimization starts. In this phase, the CH with no member changes to a typical node and joins a neighboring CH. The CH sends scheduling information to nodes that are a member of the cluster. Algorithm 4 shows the cluster improvement phase in the cluster initialization stage in MHCRP.

Route Reply and *Route Request* are essential components for constructing a route. In the preceding stage, the nodes in the first layer that are closer to the BS transmit the *route request* message to the network. Subsequently, the nodes in the second layer get this message, and this sequence of events continues until the final layer. Each of the above messages sent to request a route contains the amount of energy remaining in the CH and the number of member nodes. CHs in the first layer transmit data directly to the BS. The cost of transmitting data to BS for other CHs is calculated using Equation (9).

$$realy_0(i) = E_{TX}^{CHi,BS}(i,l,d) \quad (9)$$

Algorithm 4 Cluster Improvement Phase in the Cluster Initialization Stage in MHCRP

```
begin
  while (CT < T2)
    if state = CH and |CM[]| = 0;
      state = CM;
      select the CH from HL[];
      send a JoinCluster_Msg;
        else
          Receive JoinClusterMsg;
          store in ClusterMember[] List;
  end if
  end while
          if Sensor[i].state == ClusterHead;
              Sensor[i].state = ClusterHeadP;
              update Layer in Cluster & Assists CHnode;
              send TDMA-Msg;
            else if
              Receive TDMA-Msg;
      end if
end
```

If a CH is present between CHs and BS and it gets the *route request* message, then the cost of transferring data to the intermediate CH is computed. The decision-making process of this CH is based on many factors, including the cost of receiving information, the size of the intermediate cluster, the distance to the next step, and the availability of enough energy to receive the data packet. CH of next step is selected such that costs are minimized. This cost is calculated according to Equation (10), as shown at the bottom of the next page.

$E_{TX}^{CHi,CHj}(i,l,d)$ is the required energy for transmitting data from *CHi* to *CHj*. $E_{TX}^{CHj,Nexthopj}(j,l,d)$ is the required energy for transmitting data from *CHj* to the next hop. $E_{RX}(j,l)$ is the required energy for receiving data at node *j*. $R(j)$ is the number of CH, for which node *j* act as a relay node and receive their data. $M(j)$ is the number of member nodes in *CHj*. After selecting CH with minimum relay cost, CH transmits *route reply* message to middle CH and then data transmission is performed based on the constructed route.

In brief, node degree calculation is a critical step in our network initialization process, which comprises five phases: Delay Calculation, CH Selection, Cluster Formation, Cluster Improvement, and Route Construction. During the first phase, nodes determine the time they require to become CHs by calculating their delay time. Following the BS initial strategy announcement, each node adjusts its radius based on Equation (6) and exchanges energy levels with neighboring nodes. Subsequently, nodes determine their neighboring nodes and update their degree, which represents the number of neighbors. This degree is used in the delay time calculation, ensuring that nodes with higher connectivity (more neighbors) are appropriately considered.

D. DATA TRANSMITTING STAGE

The data transmission phase consists of two phases: intra-cluster transmitting, and inter-cluster transmitting. We hereby propose a new data transmitting phase strategy named transmission discretion license or confidence value. The aim of this strategy is to reduce invalid transmissions and finally decrease energy consumption. Thus, a node may only send data if its discretion license is computed.

Consequently, every node computes the necessary energy for data transmission before to executing the task. If the energy level is higher than that needed for sending data, the transmission discretion license is valid and then the node can transmit data. If the energy level is less than the predicted level, another destination will be selected. If a node can′t find any destination with the transmission license, it calculates the second discretion license for storing and integrating in next round.

In other words, it calculates the amount of energy needed for storing and integrating packets in the next round. If the energy level is more than that needed for integrating, the node will not send packets in the next round and will store the packet for next rounds. If a node can′t get the first and second licenses, it loses the chance to transmit or store data in those rounds and finally loses the packet without consuming energy. This way, we prevent transmissions that cause the death of nodes and reduce energy levels to zero, and finally, we prevent imperfect transmissions and will have multi-hop intra-cluster and inter-cluster transmissions. During the first phase, each individual node is situated inside a single cluster and starts transmission. Figure 5 illustrates the routing flowchart for intra-clustering in MHCRP.

In the second phase, CSMA is used for data transmitting. CSMA complements the clustering and routing mechanisms in our proposed protocol. It ensures efficient intra-cluster and inter-cluster communication by coordinating medium access. The hybrid clustering approach benefits from CSMA′s ability to manage transmissions within and between clusters, maintaining network stability and reducing communication overhead. Figure 6 illustrates the inter-cluster routing flowchart, which includes the CSMA-based data transmission process. This flowchart provides a clear depiction of how nodes sense the channel, manage their energy levels, and execute data transmission in our MHCRP. Each node checks its energy consumption for data transmission and also its energy level before transmitting. If the energy level is more than the energy consumption for transmitting, the discretion license would be approved and then the node starts transmitting. Otherwise, in order to have perfect transmission, node replacement will be done.

It should be noted that if there is no CH in inter-cluster routing, there will be no disruption during routing, so routing will be done according to the route discovery phase. The nodes located in the first layer transmit data directly to the BS by default. The timing diagram of inter-cluster data transmission is depicted in Figure 7.

IV. SIMULATION AND EVALUATION

In this section, we evaluate the proposed method. First, we introduce the simulation parameters and then compare

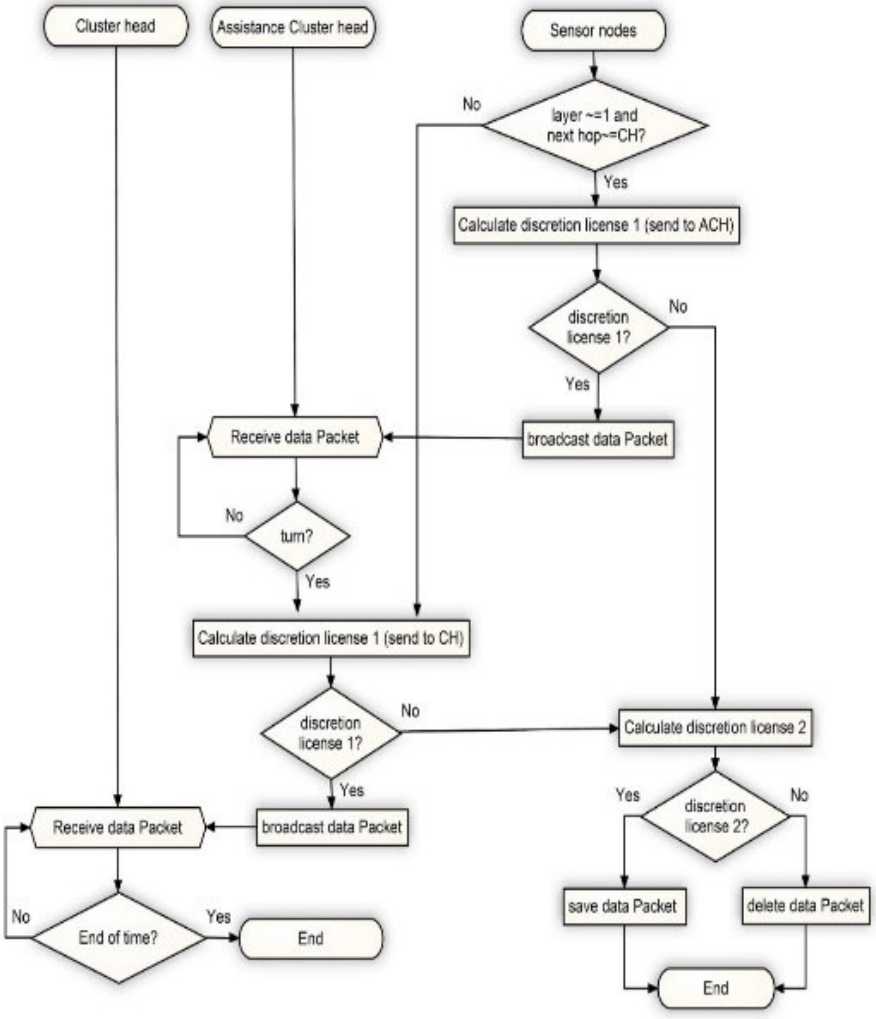


FIGURE 5. Flowchart of intra-clustering routing in MHCRP.

and evaluate the results obtained by simulations. We used the programming language MATLAB 2016 and the software was run on a machine with a 2.06GHz Pentium-IV CPU and 6GB of RAM to evaluate our proposed method and then compared it with AEHAC [18], CRBS [26], HUCL [47] and EADUC [64]. In the comparison, we compared the number of live nodes in the overall time of simulation, the stability of the network, the average energy of the network, and efficiency.

A. POTENTIAL IMPLEMENTATION CHALLENGES

In this section, we discuss several potential challenges encountered during the implementation of our proposed EH-WSNs using a novel multi-hop clustering and renewable energy-based routing protocol.

Energy Management: Efficient energy management is critical in EH-WSNs due to the variable nature of EH. Balancing energy consumption among nodes while ensuring continuous operation poses a significant challenge. Implementing dynamic energy thresholds and adaptive algorithms to adjust EH and consumption rates based on real-time data helps manage energy more efficiently.

Cluster Head Selection: The selection of CHs can lead to rapid depletion of energy in certain nodes, affecting network stability. Ensuring fair and efficient CH rotation is complex,

$$realy(i)=\begin{cases} E_{TX}^{CHi,CHj}(i,l,d)+E_{TX}^{CHj,Nexthopj}(j,l,d)+E_{RX}(j,l) & if \quad \begin{array}{l} E_{rem}(i,r)\geq E_{TX}^{CHi,CHj}(i,l,d) \qquad and \\ E_{rem}(j,r)\geq E_{TX}^{CHj,Nexthopj}(j,l,d)+(E_{RX}(j,l)\times(M(j)+R(j)+1)) \end{array} \\ Inf & Otherwise \end{cases} \tag{10}$$

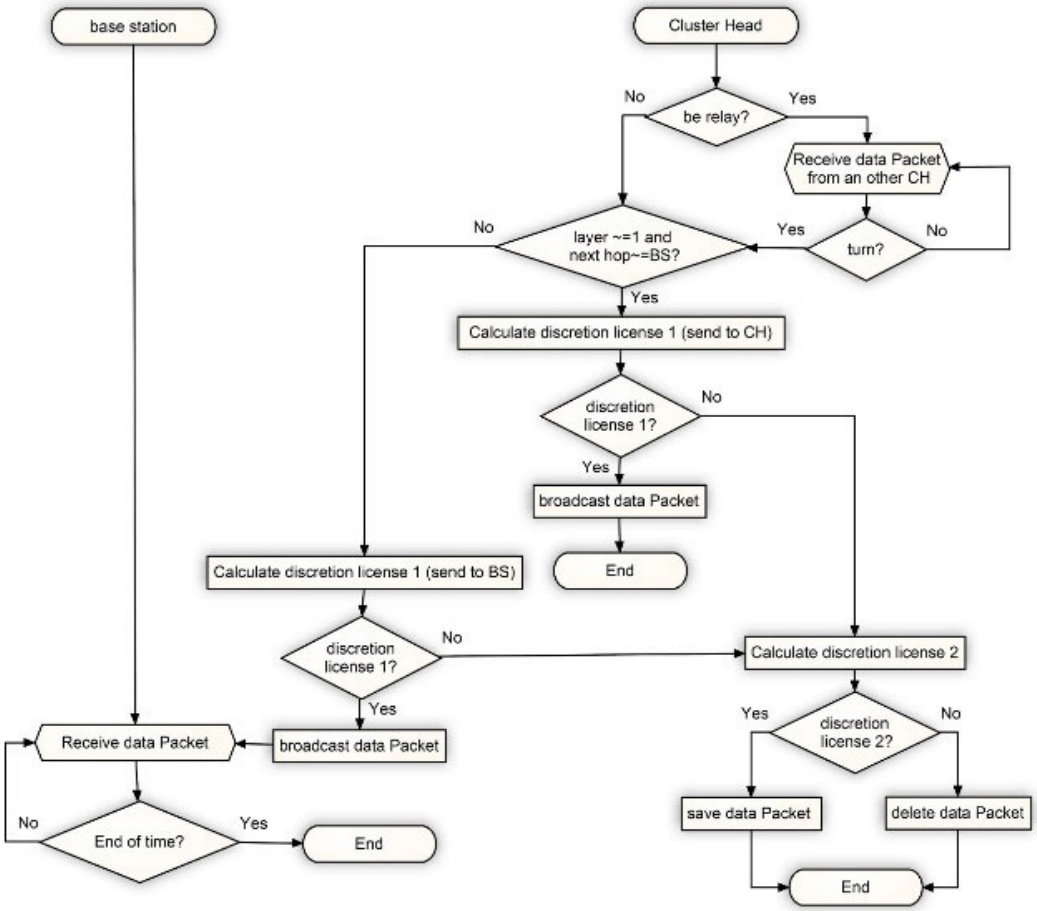


FIGURE 6. Inter-cluster routing flowchart in MHCRP.

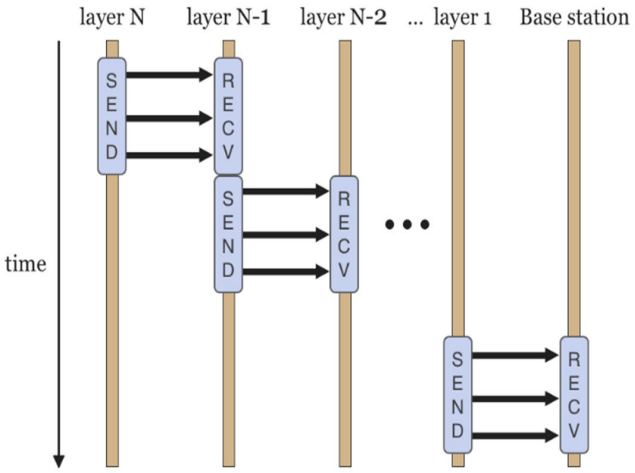


FIGURE 7. Timing diagram of an inter-cluster data transmission.

especially in large-scale networks. Utilizing a combined clustering approach with periodic re-clustering and leveraging message nodes for precise CH selection can mitigate this issue. Additionally, incorporating energy-aware metrics in the CH selection process helps distribute the energy load more evenly.

Communication Overhead: The communication overhead due to control messages for clustering and re-clustering can significantly affect network performance, especially in dynamic clustering methods. Our integrated approach minimizes overhead by reducing the frequency of re-clustering. The use of specific distance thresholds for hierarchical clustering helps maintain a balance between overhead and clustering accuracy.

Scalability: Scaling the proposed method to larger networks (beyond the simulated ($500m \times 500m$) area introduces challenges in maintaining clustering efficiency and network stability. Implementing hierarchical clustering with careful selection of distance metrics and linkage methods helps manage scalability. Additionally, optimizing the hierarchical clustering parameters for larger networks ensures effective scalability.

Synchronization Issues: Synchronizing the operations of nodes in a distributed network, particularly during CH selection and data aggregation, can be difficult, leading to potential delays and inefficiencies. Implementing robust synchronization protocols and time-slot-based communication schedules

can help mitigate synchronization issues. Ensuring that nodes operate on a synchronized schedule improves coordination and data aggregation efficiency.

Environmental Factors: Environmental factors such as varying light conditions (for solar EH) and obstacles affecting wireless signal propagation can impact network performance. Deploying redundant nodes and incorporating environmental monitoring into the EH algorithm can help adapt to changing conditions. Additionally, using multi-hop routing protocols that can dynamically adjust to environmental changes ensures reliable communication.

Hardware Limitations: Sensor nodes have limited computational capabilities and memory, which can constrain the implementation of complex algorithms and protocols. Optimizing algorithms for low-power and low-memory usage is crucial. Implementing lightweight and efficient protocols ensures that the hardware limitations do not hinder network performance.

B. SIMULATION PARAMETERS

We have mentioned two different scenarios that are shown in Table 1. EH-WSN#1 (1500, 500): Placing the BS closer to one edge of the network space introduces an asymmetry in node-to-base station distances. This scenario tests the method′s robustness and efficiency in managing communication and energy consumption across varying distances, simulating practical scenarios where BS placement may be constrained by geographical or logistical factors. EH-WSN#2 (500, 500): Here, the BS is located closer to the center of the network space, reducing the average distance between nodes and the BS. This centralized placement facilitates more efficient data aggregation and reduces communication latency. It allows us to evaluate the method′s performance under more balanced network conditions and assess its adaptability to different BS placements. EH-WSN#3 (0, 0): Placing the BS at the origin of the network space evenly distributes the node-to-base station distances, creating a symmetrical communication pattern. This scenario tests the method′s scalability and efficiency in managing communication and energy consumption across a uniformly distributed network, providing insights into its performance under idealized conditions. These scenarios provide a holistic view of the method's strengths and potential areas for improvement, ensuring its applicability in various real-world EH-WSN deployments.

The parameters used in the simulation of the proposed method are shown in Table 2. We utilized homogeneous nodes, each equipped with an initial energy of 0.5 Joules started at 12 AM. The nodes are designed to harvest energy from solar sources, leveraging the ambient light available in the environment. Homogeneous nodes ensure uniformity in energy consumption patterns and network behavior, simplifying the analysis and comparison of our proposed routing protocol′s efficiency and performance.

Difference between Message Size and Data Packet Size:

1. Data Packet Size: Data packets refer to the units of data that nodes transmit during the regular communication process. These packets contain the actual sensor data collected by the nodes, are encapsulated in data packets for transmission to the sink or other nodes. The packet size in our simulations is selected to reflect real-world scenarios where data packets can be relatively large, especially in applications requiring rich data such as environmental monitoring or video surveillance.

2. Message Size: Control messages are smaller units of information exchanged between nodes to coordinate network operations. These messages are crucial for network management tasks, including Cluster Formation: Messages sent during the clustering process. Route Discovery: Messages used in establishing and maintaining routing paths. Energy Management: Messages that relay information about node energy levels.

The value of λ for the second and third layers is assumed to be 1.25 and for the fourth layer, it is assumed to be 1.75. So, closer clusters to the BS are smaller and CHs have more energy for routing higher-level packets toward the BS. In order to obtain RL_{max}, it is assumed that at best state, K_{opt} CHs cover the whole network. Accordingly, it can be said that the area that each CH covers is equal to Equation (11).

$$A_{cluster} = \frac{A_{total}}{k_{opt} \times N} \tag{11}$$

A total is total area of the network. K_{opt} is optimum number of CHs in the network, where in [65], it is equal to 5% of all nodes. N is total number of nodes. Assuming best state for obtaining maximum radius of each CH, area of circle is considered to be $A = \pi r2$ and maximum radius is obtained from Equation (12).

$$Rl_{Max} = \sqrt{\frac{A_{cluster}}{\pi}} \tag{12}$$

TABLE 1. Simulation scenarios.

Network	Base Station	Number of Nodes	Network Space
EH-WSN#1	(1500, 500)	100	1 Km × 1 Km
EH-WSN#2	(500, 500)	50	1 Km × 1 Km
EH-WSN#3	(0, 0)	150	1 Km × 1 Km

TABLE 2. Parameter settings for simulation.

Parameters	Value
E_{elec}	$50\ nJ/bit50$
E_{fs}	$10\ pJ/bit/m^2$
E_{mp}	$0.0013\ pJ/bit/m^4$
E_{DA}	$5\ nJ/bit/message$
Data packet size	$1000\ byte$
Packet header size	$25\ byte$
Control Message size	$50\ byte$
Lower energy for harvesting	$0.1j$
Upper energy for harvesting	$1\ j$
Initial energy	$0.5j$
The battery capacity	$0.5j$
α, β	0.333

Integrating Equation (11) and Equation (12), RL_{max} is obtained from Equation (13):

$$Rl_{Max} = \sqrt{\frac{A_{\text{total}}}{(k_{opt} \times N) \times \pi}} \tag{13}$$

We ran the simulations 50 times and will show the average results.

C. PROPOSED PROTOCOL OPERATIONS

Purpose of this study is to determine which strategy has been selected by the proposed protocol for clustering in each of three different simulation scenarios and to see in how many rounds of data transmission, Cluster initialization stage has not been performed due to the proper energy of CHs to reduce overhead. In determining strategy, the point that strategy selection by BS depends on number of nodes, nodes' distribution and their location in the network (distance of furthest and nearest node from BS in Equations (4) and (5), location of BS, network dimension and radius of nodes Equations (13) is essential.

In the first simulation scenario, the BS employed the first strategy for clustering in 38% of cases. This means that in the first scenario, in 38% of simulations, the proposed protocol has used information on neighbors of a node to determine CH. In addition, in other 62% of cases, since nodes are close to each other, information about neighbors is not used for reducing CH. This difference is due to different locations of nodes in the network. In the second scenario, the BS is located in the center of the network, resulting in a larger concentration of nodes that are connected to the BS. Consequently, in all simulations, the BS employs the second technique to construct clusters without relying on information from neighboring nodes. In the third case, the BS is located in the corner of the network. In this scenario, the BS consistently employs the initial method and nodes exchange information with their adjacent nodes. This is due to the expansion of the network's node count and the extensive coverage of most network locations, which directly impacts Equations (4) and (5).

The emphasis in cutting overhead is on adjusting CH only when their energy is improper. For this reason, sending control messages requires less overhead and energy. Considering that the suggested protocol is designed so that cluster initialization step is carried out anytime energy of a CH falls below energy threshold. But in this situation, nodes should send a control message to the main data (which is examined in *Section E)* that includes energy information; this not only lowers but also increases the energy of the control message. This lowers the energy consumption of control messages in one cluster initialization stage, including *node msg*, *head msg*, *join msg*, TDMA *msg*, *route request msg*, and *route reply msg*, in simulations, in 30.9%, 55.2%, and 23.1% of rounds, respectively.

D. NETWORK AND ROUND STABILITY

To increase efficiency, it is necessary to send more data to the BS and to receive more data in the BS, it is necessary to prevent the death of nodes as much as possible. So, it is possible to improve efficiency through increasing network stability. The First Node Dies (FND) is a good parameter to measure the stability of the protocol. Figures 8 show the stability of the simulated protocols for Scenarios 1, 2 and 3. AEHAC and CRBS protocols are designed for EH-WSN and support one-hop transmission, while the two other protocols (HUCL and EADUC) are designed for WSNs and support multi-hop transmission.

Considering large dimensions of the network, it should be said that single-hop protocols are not suitable for this environment. On the other hand, it can be seen that performance of single-hop protocols does not change stability much compared to multi-hop protocols. In the second scenario where the BS is at the center and the distance between CH and BS is reduced, two single-hop protocols designed for MHCRP, give better FND.

This shows that good protocols of WSNs can′t work as well in EH-WSN because they don′t consider the EH factor in clustering. Considering Tables 3 and 4, it can be said that the two protocols AEHAC and CRBS have weaker performance than HUCL and EADUC. This is due to the larger network space and longer transmission distances. Since these two protocols support one-hop transmission, farther nodes to the BSs are more likely to lose energy. As a result, network stability decreases drastically. Our proposed method could operate in three different environments and reach a good performance and high stability. Tables 3, 4 and 5 summarize the round performance and protocol stability of the different scenarios. Mentioned criteria are FND, the death of 10% of nodes and the death of 20% of nodes. The results obtained demonstrate that the suggested protocol has the ability to delay the occurrence of FND and PND, while also increasing the transmission of packets when these requirements are met. This enhanced stability is achieved by prioritizing the idea that nodes without sufficient energy levels or EH status should not be selected as CHs. Due to the higher energy use of the CH compared to other nodes, the focus on this concept resulted in a more equitable distribution of energy usage across nodes throughout the simulation. Due of the increased energy consumption at longer distances, it is important to exercise caution while selecting a CH. The findings obtained indicate that the suggested protocol has the capability to postpone the demise of the first node, as well as 10% and 20% of the total nodes.

E. NUMBER OF LIVE NODES

"Alive nodes" in Table 6 refers to the average number of nodes that, under various situations, stay alive and functional over the whole simulation time. These nodes have enough energy levels to carry out the sensing, processing, and

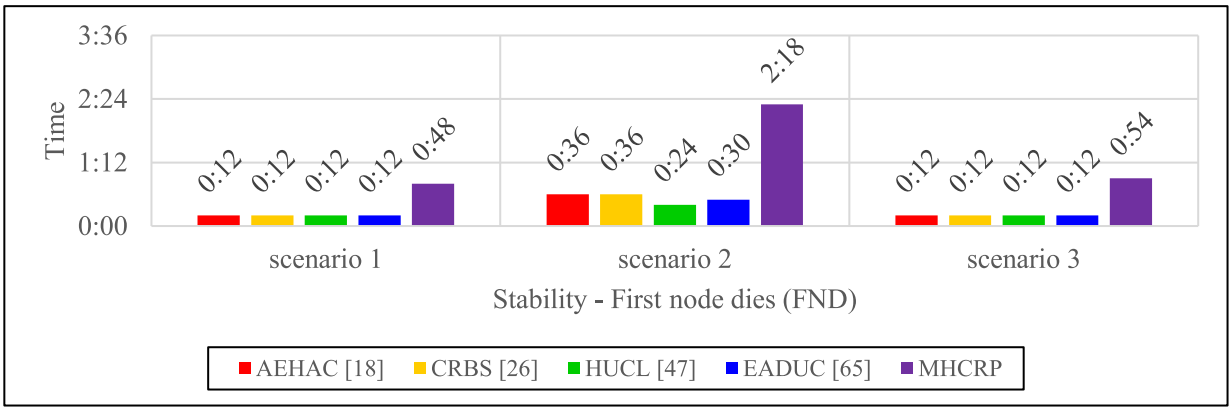


FIGURE 8. Network stability in senarios EH-WSN # 1, 2, 3.

TABLE 3. Simulation results for scenario EH-WSN#1.

Protocol	FND (100 Nodes)		10% PND (90 Nodes)		20% PND (80 Nodes)	
	Time	Packets	Time	Packets	Time	Packets
AEHAC [18]	00 h : 12 min	177.4	00 h : 12 min	177.4	00 h : 12 min	177.4
CRBS [26]	00 h : 12 min	154.8	00 h : 12 min	154.8	00 h : 12 min	154.8
HUCL [47]	00 h : 12 min	191.4	00 h : 18 min	300.8	00 h : 36 min	516.8
EADUC [65]	00 h : 12 min	197.6	00 h : 48 min	735.3	01 h : 12 min	1064.2
MHCRP	**00 h : 48 min**	**816.9**	**08 h : 30 min**	**7164.9**	**N**	**N**

TABLE 4. Simulation results for scenario EH-WSN#2.

Protocol	FND (50 Nodes)		10% PND (45 Nodes)		20% PND (40 Nodes)	
	Time	Packets	Time	Packets	Time	Packets
AEHAC [18]	00 h : 36 min	288.8	01 h : 00 min	485.4	01 h : 18 min	599.9
CRBS [26]	00 h : 36 min	288.2	00 h : 54 min	432.5	01 h : 12 min	559.7
HUCL [47]	00 h : 24 min	191.4	00 h : 42 min	325.3	01 h : 00 min	453.9
EADUC [65]	00 h : 30 min	221.5	00 h : 54 min	442	01 h : 24 min	643.2
MHCRP	**02 h : 18 min**	**1150**	**04 h : 12 min**	**2037.3**	**05 h : 30 min**	**2618.6**

TABLE 5. Simulation results for scenario EH-WSN#3.

Protocol	FND (150 Nodes)		10% PND (135 Nodes)		20% PND (120 Nodes)	
	Time	Packets	Time	Packets	Time	Packets
AEHAC [18]	00 h : 12 min	275.4	00 h : 12 min	275.4	00 h : 18 min	371.5
CRBS [26]	00 h : 12 min	292.2	00 h : 18 min	391.3	00 h : 24 min	471.8
HUCL [47]	00 h : 12 min	310.9	00 h : 35 min	932.8	01 h : 12 min	1666.6
EADUC [65]	00 h : 12 min	304.3	01 h : 00 min	1410.7	01 h : 35 min	2302.7
MHCRP	**00 h : 54 min**	**1370**	**03 h : 36 min**	**5035.4**	**04 h : 54 min**	**6854.8**

communication tasks that are desired of them. A network is more robust and resilient the more viable nodes it has as it shows better energy management, less energy depletion, and longer network lifespan.

As seen, the suggested approach has an average of more accessible nodes than alternative approaches. More than 95% of all the nodes in the first scenario are alive, while in the second and third situations, more than 86% of all the nodes are alive throughout simulation. Actually, in scenario 1 over 95% and in scenarios 2 and 3 over 86% of the nodes transmit data on average. Stability of the network is confirmed by this characteristic. Figures 9, 10 and 11 show the quantity of nodes that are accessible during simulation.

MHCRP outperforms other protocols, according to the results, and it may expand the number of nodes that are accessible during simulation. The rationale is that the suggested protocol prevents node mortality by balancing energy consumption between them. Furthermore, the energy consumption is the primary criteria used by the transmission discretion threshold license during the stability phase. This manner, it saves energy and avoids node death by foreseeing pointless transfers. Thus, only practical transmissions are carried out in the suggested protocol.

The MHCRP effectively integrates EH mechanisms, ensuring that nodes continuously replenish their energy stores, thereby extending their operational lifespan. By dynamically

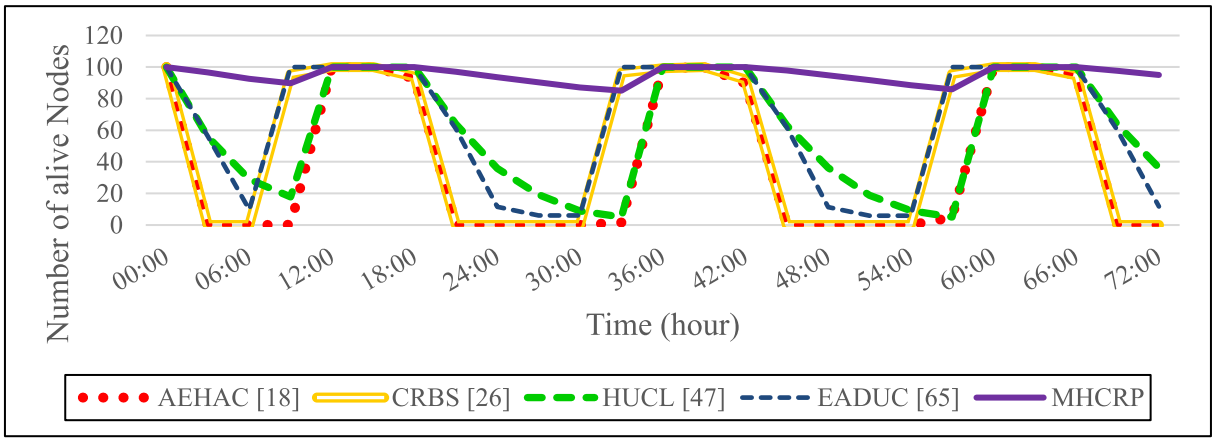


FIGURE 9. Average number of available nodes in a round of EH-WSN#1.

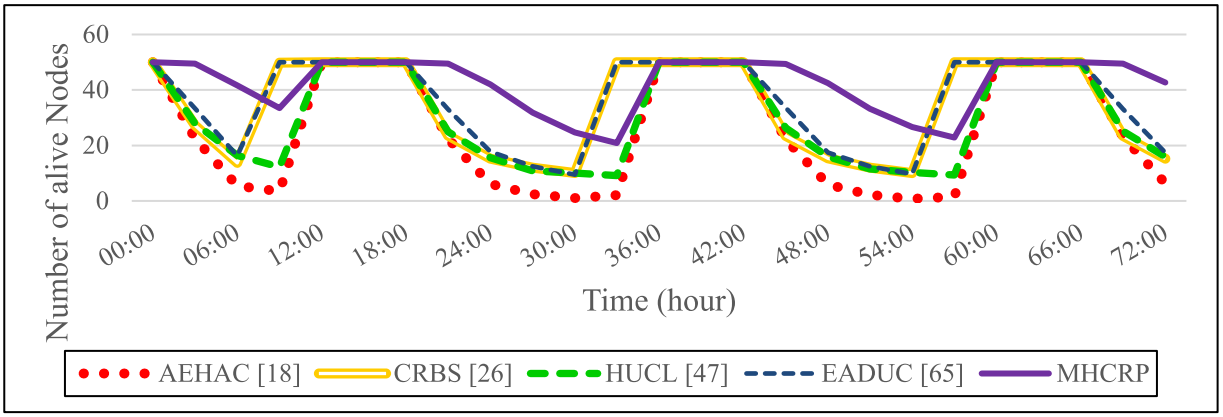


FIGURE 10. Average number of available nodes in a round of EH-WSN#2.

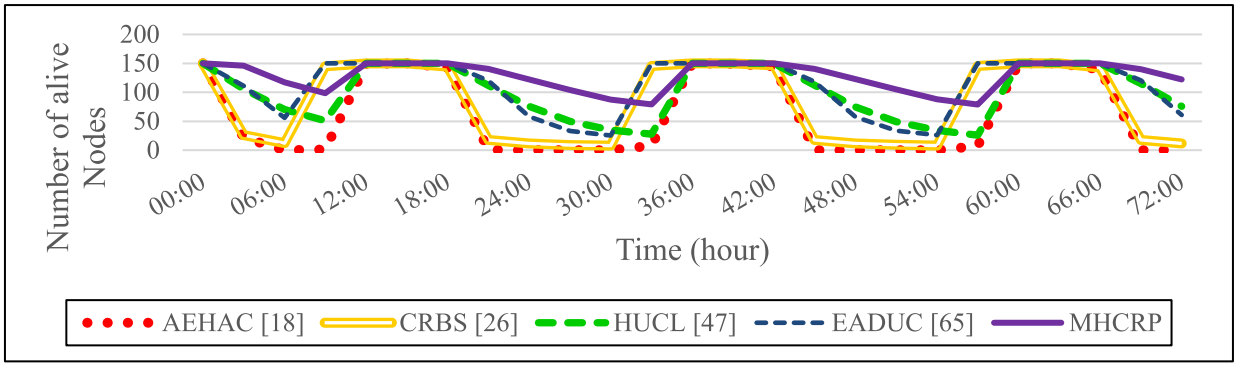


FIGURE 11. Average number of available nodes in a round of EH-WSN#3.

adjusting CH roles and considering nodes' remaining energy, the protocol prevents early depletion of energy in any single node, contributing to a higher number of viable nodes. MHCRP reduces communication overhead by optimizing the routing paths and clustering formation. This leads to lower energy consumption per node for communication tasks, further extending the nodes' operational time.

F. THE AMOUNT OF ENERGY IN NODES

Figures 12, 13 and 14 show the average energy of live nodes during the simulation. It can be said in other protocols, farther nodes from the BS are faced with a sharp decline in energy level and therefore death, and closer nodes to the BS lose energy gradually. But in the proposed protocol, in addition to determining an appropriate CH, energy consumption is

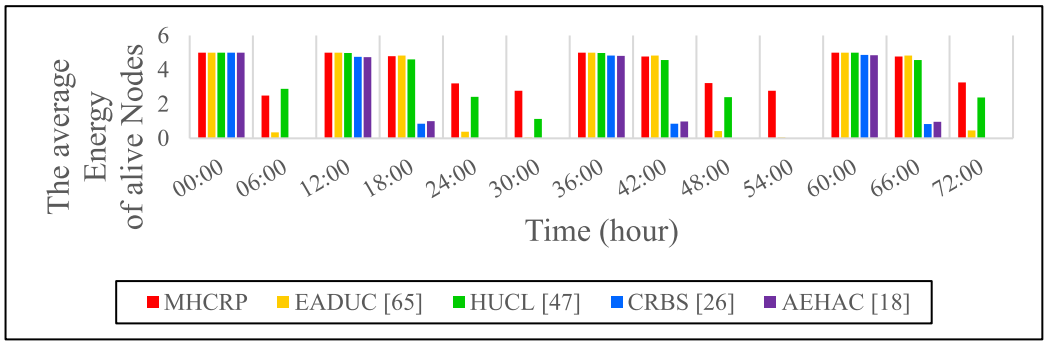


FIGURE 12. The average energy of live nodes in a round of EH-WSN#1.

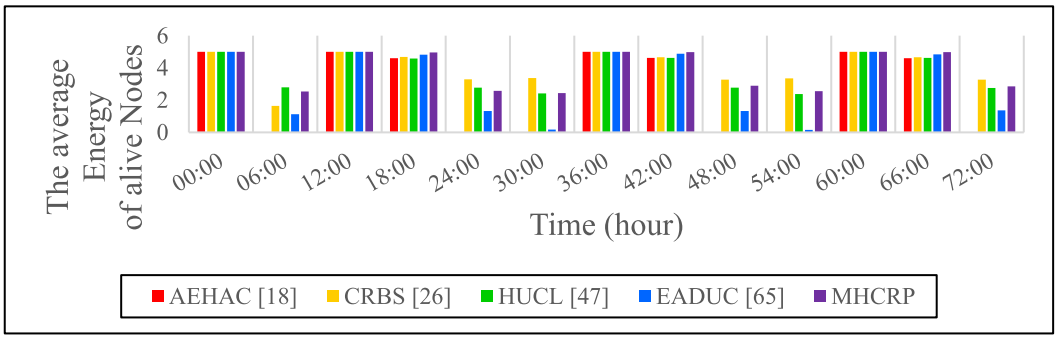


FIGURE 13. The average energy of live nodes in a round of EH-WSN#2.

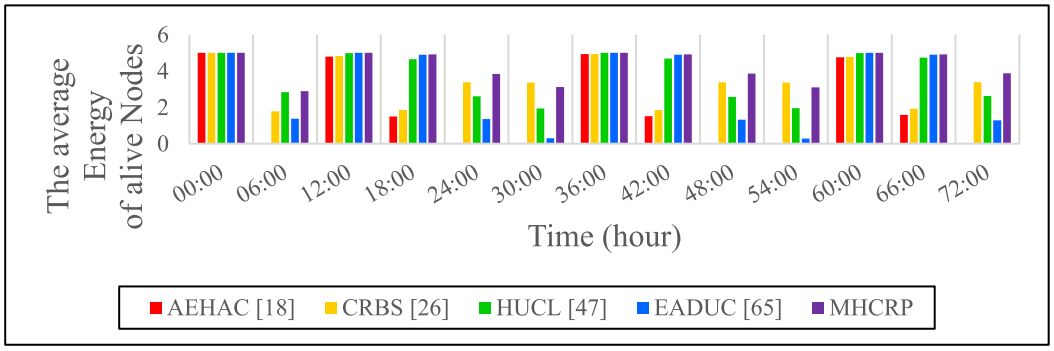


FIGURE 14. The average energy of live nodes in a round of EH-WSN#3.

TABLE 6. Average number of alive nodes during simulation.

Protocol	Scenario 1	Scenario 2	Scenario 3
AEHAC [18]	41.4	27.5	63.8
CRBS [26]	41.2	31.3	70.7
HUCL [47]	62.6	31.5	105.9
EADUC [65]	57.7	32.8	101.7
MHCRP	**95.9**	**43.2**	**130.5**

divided between nodes and signals are facing less depression due to utilizing multi-hop transmission which leads to shorter transmission distance and less energy for transmission. So, by avoiding direct transmission over long distances and choosing an appropriate CH the proposed protocol prevents sudden loss of energy. This technique achieves equilibrium in energy consumption between nodes that are both distant and closer, resulting in enhanced stability and ultimately improved efficiency. *Section B* of this document states that one of its objectives is to minimize the burden of control messages. Considering the proposed mechanism, evaluation of the protocol in this section is considerable. Since energy consumption of control message in single-hop and multi-hop protocols is different, this section compared the proposed protocol with two multi-hop methods of HUCL and EADUC. HUCL and EADUC protocols are multi-hop protocols that try to reduce the overhead of control messages in the network. Table 7 shows energy consumption for control messages in

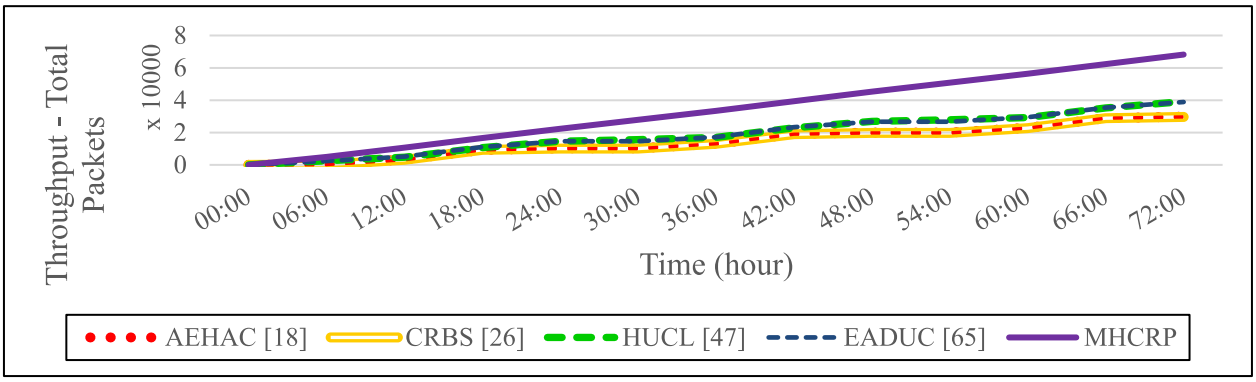


FIGURE 15. Number of produced packages in a round of EH-WSN # 1.

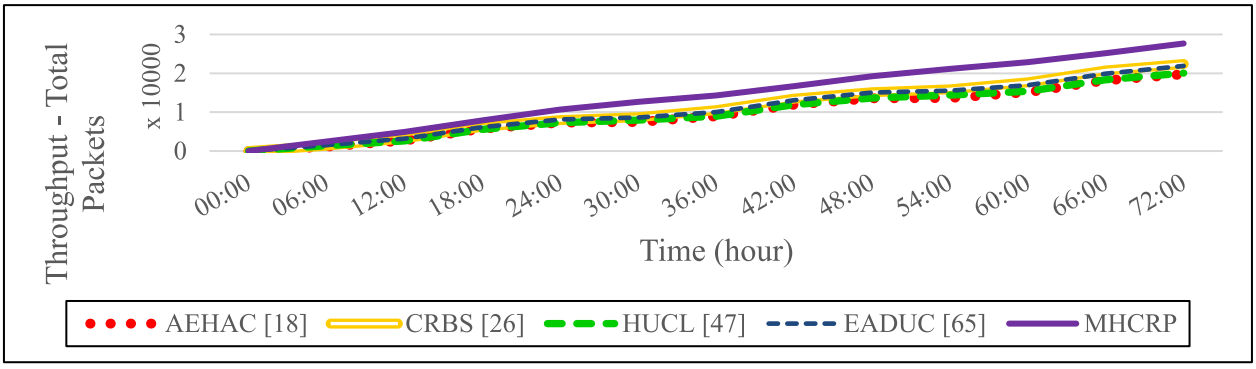


FIGURE 16. Number of produced packages in a round of EH-WSN # 2.

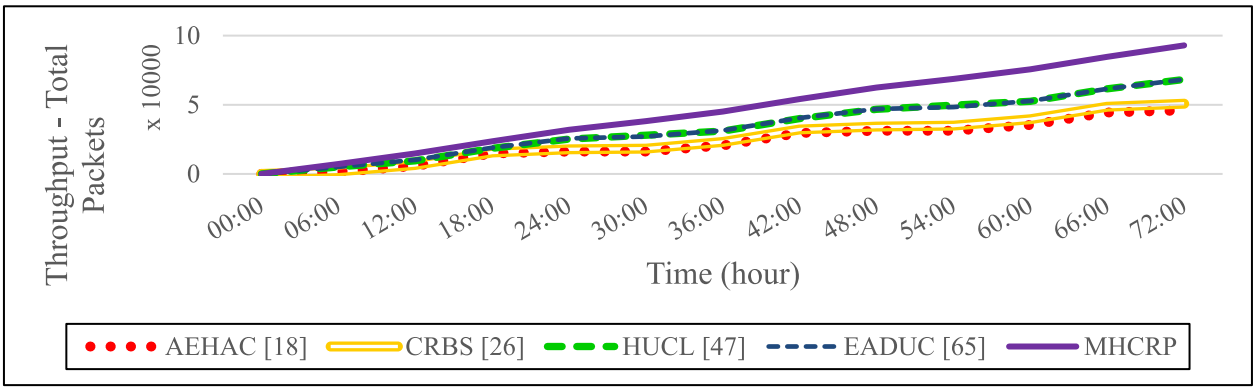


FIGURE 17. Number of produced packages in a round of EH-WSN # 3.

TABLE 7. Total energy consumption for control message in multi-hop protocols.

Protocol	Scenario 1	Scenario 2	Scenario 3
HUCL [47]	642.7 j	258.2 j	867.5 j
EADUC [65]	1292.1 j	949 j	1770.2
MHCRP	**374.9 j**	**72 j**	**564.5**

different simulation scenarios. Results show that the proposed protocol has reduced the overhead of the network and energy consumption.

G. EFFICIENCY

Figures 15, 16 and 17 show the produced packets in a round, and all of them indicate the superiority of the proposed protocol. The proposed method could produce more packets during simulation. As some reasons for this increased efficiency, we can name balanced energy consumption, increased stability and increased number of available nodes.

In EH-WSNs, a lower threshold is predicted and based on this threshold, the energy level of nodes would be checked at the beginning of each round to determine whether it is lower or higher than the threshold. If the energy level of a node is lower than the threshold, that node is blocked and goes into charging mode until reaching an acceptable level. Other benefits of this lower threshold are that produced packets in EH-WSNs are sent to their destinations with the least risk. Because transmissions that lead to zeroing the energy (of imperfect transmissions) are not allowed.

TABLE 8. Average packet loss and average throughput for EH-WSN#1.

Time	AEHAC [18]			CRBS [26]			HUCL [47]			EADUC [65]			MHCRP		
	made	loss	%	made	loss	%	made	loss	%	made	loss	%	made	loss	%
06:00	0	-	-	0	-	-	28.1	27.9	%99.2	4.8	4.7	%97.9	**92.6**	**0**	**%0**
12:00	100	76.7	%76.7	100	71.9	%71.9	100	2.7	%2.7	100	0.7	%0.7	**100**	**0**	**%0**
18:00	92.7	72.8	%78.5	92.7	78.4	%84.5	99.9	4.1	%4.1	100	1.2	%1.2	**100**	**0**	**%0**
24:00	0	-	-	0	-	-	35.1	33.6	%95.7	5.9	5.9	%100	**93.6**	**0**	**%0**
30:00	0	-	-	0	-	-	6.7	6.7	%100	0	-	-	**87**	**0**	**%0**
36:00	99.2	74.7	%75.3	99.2	71.7	%72.2	99.9	1.5	%1.5	100	0.6	%0.6	**100**	**0**	**%0**
42:00	89.7	69.4	%77.3	91.3	76	%83.2	100	5.6	%5.6	99.9	2.1	%2.1	**100**	**0**	**%0**
48:00	0	-	-	0	-	-	35.1	33.6	%95.7	5.8	5.7	%98.2	**94.7**	**0**	**%0**
54:00	0	-	-	0	-	-	6.7	6.7	%100	0	-	-	**88.4**	**0**	**%0**
60:00	100	73.8	%73.8	100	72.7	%72.7	100	1.4	%1.4	100	0.7	%0.7	**100**	**0**	**%0**
66:00	95	75.5	%79.4	94.6	79.2	%83.7	100	4.5	%4.5	100	2.7	%2.7	**100**	**0**	**%0**
72:00	0	-	-	0	-	-	35.1	33.7	%96	6.1	6.1	%100	**94.9**	**0**	**%0**

TABLE 9. Average packet loss and average throughput for EH-WSN#2.

Time	AEHAC [18]			CRBS [26]			HUCL [47]			EADUC [65]			MHCRP		
	made	loss	%	made	loss	%	made	loss	%	made	loss	%	made	loss	%
06:00	5.4	0.46	%8.51	13.7	0.4	%2.91	15.8	0.28	%1.77	13.8	0.62	%4.49	**41.6**	**0**	**%0**
12:00	50	0	%0	50	0	%0	50	0.1	%0.2	50	0	%0	48.6	0	%0
18:00	50	0.16	%0.32	50	0.02	%0.04	50	0.82	%1.64	50	0.1	%0.2	48.6	0	%0
24:00	8.8	0.14	%1.59	16.8	0.08	%0.47	17.1	0.14	%0.81	18.8	0.2	%1.06	**44.9**	**0**	**%0**
30:00	1	0.08	%8	10.1	0.04	%0.39	9	0.06	%0.66	2.8	0.02	%0.71	**24.6**	**0**	**%0**
36:00	50	0	%0	50	0	%0	50	0.08	%0.16	50	0	%0	38.1	0	%0
42:00	50	0.14	%0.28	50	0.06	%0.12	50	0.6	%1.2	50	0.06	%0.12	39.5	0	%0
48:00	5.8	0.26	%4.48	15.3	0.16	%1.04	15.2	0.26	%1.71	15	0.26	%1.73	**39.7**	**0**	**%0**
54:00	0.7	0	%0	10.1	0.06	%0.59	9.2	0.12	%1.3	2.9	0.22	%7.58	**25.2**	**0.04**	**%0.2**
60:00	50	0	%0	50	0	%0	50	0.06	%0.12	50	0	%0	37.6	0	%0
66:00	50	0.16	%032	50	0	%0	50	0.52	%1.04	50	0.08	%0.16	39.8	0	%0
72:00	6.4	0.06	%0.93	15.2	0.14	%0.92	15.2	0.4	%2.63	14.9	0.28	%1.87	**37.7**	**0**	**%0**

TABLE 10. Average packet loss and average throughput for EH-WSN#3.

Time	AEHAC [18]			CRBS [26]			HUCL [47]			EADUC [65]			MHCRP		
	made	loss	%	made	loss	%	made	loss	%	made	loss	%	made	loss	%
06:00	0.1	0	%0	12.1	0.2	%1.6	69.1	24.9	%36	48.3	5.3	%10.9	**117.2**	**0**	**%0**
12:00	149.4	77.7	%52	149.5	70.4	%47	150	2.6	%1.7	150	0.1	%0.06	**150**	**0**	**%0**
18:00	142.5	78.1	%54.8	144.1	84.9	%58.9	149.9	5.8	%3.8	150	0.2	%0.13	**150**	**0**	**%0**
24:00	0.02	0	%0	11.3	0.02	%0.17	74.1	29.1	%39.2	50.6	8.7	%17.1	**121.9**	**0**	**%0**
30:00	0	-	-	7.9	0.04	%0.5	30.6	10.8	%35.2	10.3	0.8	%7.7	**87.3**	**0**	**%0**
36:00	150	77.2	%51.4	150	70.8	%47.2	150	1.8	%1.2	150	0.1	%0.06	**150**	**0**	**%0**
42:00	144.7	81.3	%56.1	146.3	86.9	%59.3	150	5.4	%3.6	150	0.3	%0.2	**150**	**0**	**%0**
48:00	0	-	-	11.4	0.04	%0.3	72.8	33.4	%45.8	49.3	8.1	%16.4	**123**	**0**	**%0**
54:00	0	-	-	7.9	0.04	%0.5	30	10.7	%35.6	9.7	1.1	%11.3	**88.1**	**0**	**%0**
60:00	150	77.6	%51.7	150	70.9	%47.2	150	1.9	%1.2	150	0.1	%0.06	**150**	**0**	**%0**
66:00	139.2	75.5	%54.2	142.2	82.8	%58.2	150	5.3	%3.5	150	0.2	%0.13	**150**	**0**	**%0**
72:00	0	-	-	11.4	0.04	%0.35	73.9	31.8	%43	53.2	10.3	%19.3	**122.1**	**0**	**%0**

Imperfect transmissions have a lot of consequences. First, sending a packet that leads to the death of a node is incompletely received in the destination; second, energy is consumed for an imperfect transmission; and third, besides imperfect transmission and useless energy consumption, an unnecessary overhead is imposed on the network traffic. The aim of EH-WSN is to solve these challenges forever. The proposed method claims that by taking into account the discretion threshold and storing (integration) threshold, there will be no cost for imperfect transmission. In other words, all energy in the proposed method would be spent on healthy transmissions. The lower threshold in EH-WSNs reduced this rate, the strategy of the proposed method prevents the death of nodes in the data transmission phase. The proposed method postpones sending data that leads to the death of nodes and also avoids invalid packet transmission. So, in fact, MHCRP avoids useless transmissions at the cost of increased delay.

Lost packets refer to packets that are flawed or have not been successfully received during the transfer of data. Quantifying the quantity of dropped packets is crucial for assessing the effectiveness of a parameter. Tables 8, 9, and 10 show the mean values of created packets, missing packets, and lost packets at various time intervals.

The findings indicate that the suggested protocol has a lower number of lost packets compared to the other two techniques. It is important to note that the suggested protocol ensures reliable data transfer with little expenses and depends on gathered energy in following iterations.

V. CONCLUSION

Developing technology in recent years, sensor networks have been used widely in various fields. A new category of WSNs with the ability to harvest renewable energies (like solar, wind, vibration, etc.) from the environment is emerging. As long as energy consumption in these networks is less than

EH from the environment, nodes don′t die as a result of finishing energy. Compared to battery-powered WSNs, EH-WSNs have unique characteristics that existing routing protocols for WSNs aren′t suitable here. In this paper, we proposed a novel multi-hop clustering and renewable energy-based routing protocol for EH-WSN, in which clustering is done in a hybrid distributed-centralized manner based on energy status and the amount of harvested energy. The routing between nodes, CHs, and BS is based on multi-hop real-time routing. Extensive results show that NERY effectively improves the stability and efficiency of the network. The proposed method could also increase the number of available nodes and balance energy consumption. Results indicate the effectiveness of the proposed algorithm and its ability to send more packets to the BS with high accuracy. Future work could enhance the proposed protocol by defining new criteria for nodes joining CHs, such as considering the distance from the CH, the current number of members, the energy level of CHs, and the distance between CHs and the BS. These improvements could further optimize network performance and extend the lifespan of EH-WSNs.

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