A Distributed Energy-Efficient Clustering Routing Protocol with Dynamic Round-Length for Wireless Sensor Networks

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ABSTRACT

Due to resource constraints, especially limited energy and network dynamics, the design and implementation of efficient and reliable routing protocols for Wireless Sensor Networks (WSNs) has become a challenging task. Several routing protocols, particularly cluster-based ones, have been developed with the potential to significantly increase network lifetime. However, these protocols still have drawbacks, such as reliance on probabilistic and centralized clustering mechanisms, single-hop communication within clusters, periodic re-clustering, and static round lengths. To address these issues, this paper presents the Distributed Energy-Efficient Clustering Routing Protocol with a Dynamic Round Length (DEECRP-DRL) for WSNs. To deal with the hotspot problem, a clustering fitness function is defined to determine the optimal Cluster Heads (CHs) and to form unequal clusters based on residual energy, intra-cluster distance, and inter-cluster distance metrics. Meanwhile, a routing fitness function is used to select the best relay nodes for efficient multi-hop data routing. The round duration is dynamically calculated based on the residual energy of CHs to minimize the overhead caused by the re-clustering process. The simulation results using OMNeT++ show that DEECRP-DRL outperforms existing algorithms across various scenarios, including the impact of Base Station (BS) location and network scalability.

Keywords-clustering; energy efficiency; network lifetime; round-length; routing protocols; wireless sensor networks

I. INTRODUCTION

WSNs have become a vital technology in recent decades, with applications in various fields, such as environmental monitoring, healthcare, industrial automation, and military surveillance [1]. A WSN is composed of many small, low-cost, low-power embedded devices known as Sensor Nodes (SNs), and a resource-unlimited BS [1]. The SNs monitor and control environmental conditions and wirelessly transmit the collected data to the BS [2]. SNs can be deployed deterministically or randomly, particularly in harsh or inaccessible areas [3]. WSNs can be classified into two types: homogeneous networks, where all SNs have similar resources, and heterogeneous networks, where SNs differ in energy capacity, link quality, and computational power [4]. The latter is often preferred, as it enhances network lifetime and reliability [5]. A major constraint in WSNs is the limited energy, which is often supplied by non-rechargeable and non-replaceable batteries [6, 7]. Energy consumption is significantly influenced by the distance between SNs and the BS, since SNs expend more energy for data transmission [8]. Furthermore, WSNs have dynamic topologies in which SN failures and environmental conditions can disrupt network connectivity, making the design and implementation of efficient routing even more challenging. Large-scale WSNs further complicate routing due to the vast number of deployed SNs [9].

To address these challenges, clustering-based routing protocols have been widely adopted [10]. Clustering protocols divide the network into sub-networks and elect CHs as leaders of these sub-networks—called clusters—to improve network performance [11]. Clustering offers multiple advantages: it reduces communication overhead, improves load balancing among SNs, aggregates data, and minimizes redundant data transmissions [12]. However, clustering presents its own challenges, particularly unbalanced energy consumption, as CHs bear a heavier workload [13]. To mitigate energy imbalance, most clustering protocols incorporate re-clustering mechanisms [14]. These protocols operate in rounds, where SNs periodically exchange information to elect new CHs in each round. However, frequent re-clustering incurs significant energy overhead and increases overall energy consumption [1]. A round consists of a clustering phase, where CHs are selected, followed by a data transmission phase. The round length (i.e., round duration) refers to the number of data transmission cycles that occur before re-clustering is triggered. A short round length leads to frequent re-clustering, which causes high energy overhead, whereas a long round length may result in unbalanced energy consumption among SNs. However, most existing protocols do not dynamically adjust round length based on network conditions, which affects energy efficiency [14].

Numerous clustering protocols have been proposed in the literature [1, 2]. The Low-Energy Adaptive Clustering Hierarchy (LEACH) is the earliest and most popular energy-efficient clustering protocol [15]. In LEACH, SNs make a probabilistic decision on whether to become CHs. Rounds are static, and CHs change dynamically without considering their residual energy. Various LEACH-based enhancements have been proposed, such as LEACH-EP [16], which optimizes CH election and dynamically adjusts round duration through energy prediction. The Hybrid Energy-Efficient Distributed Clustering (HEED) protocol, proposed in [17], selects CHs based on both residual energy and communication cost. It ensures uniform CH distribution and avoids random selection, resulting in more stable clusters and improved energy efficiency. The Stable Election Protocol (SEP), proposed in [18] for heterogeneous WSNs, introduces Advanced Nodes (ANs) with higher energy to extend network lifetime. CHs are elected probabilistically, giving higher-energy nodes a greater chance of selection, but SEP does not dynamically adjust CH election based on residual energy. The Distributed Energy-Efficient Clustering (DEEC) protocol, proposed in [19], dynamically adjusts CH election probabilities based on each node's residual energy and the average network energy. This results in better load balancing and a longer network lifetime. Authors in [20] propose the Distributed Clustering Algorithm Guided by the BS (DCAGBS), which dynamically forms clusters and maintains the same CHs until the first node dies. When this occurs, the BS broadcasts an updated skip value that defines how long an elected SN remains a CH. Alternatively, authors in [21] propose the Optimized One-Step Clustering (OPOC) protocol, which employs Particle Swarm Optimization (PSO) and energy prediction to pre-compute the cluster schema, reducing energy overhead from periodic re-clustering. Authors in [22] propose an Ant Colony Optimization (ACO)-based PSO-ACO protocol that integrates PSO for CH formation and ACO for path selection to optimize distance, node degree, and energy.

Although these protocols improve energy efficiency, they suffer from several significant drawbacks, such as static round duration, single-hop data transmission, and probabilistic CH selection. To overcome these limitations, the current study proposes DEECRP-DRL for WSNs. DEECRP-DRL is designed to optimize both energy consumption and overhead to enhance network lifetime. It introduces two novel fitness functions:

- **Clustering Fitness Function (FFc):** Evaluates residual energy, intra-cluster distance, and inter-cluster distance to select the best CHs in a distributed and adaptive manner.
- **Routing Fitness Function (FFr):** Evaluates residual energy and inter-cluster distance to dynamically select the next-hop relay node for routing data from SNs to the BS in a multi-hop manner.

Furthermore, DEECRP-DRL efficiently manages energy by adopting dynamic-length rounds based on residual energy.

The OMNeT++ simulator was used to compare three protocols—DEECRP-DRL, LEACH, and LEACH-EP—under different scenarios. The results showed that DEECRP-DRL outperforms the other protocols in terms of energy consumption and, consequently, network lifetime.

II. SYSTEM MODEL

A. Network Model

The WSN model is designed based on the assumption according to which: SNs in the network are distributed within a square area. SNs are heterogeneous in terms of energy. The energy depletion of an SN leads to its network exclusion, as its battery cannot be recharged or replaced. Each SN can function as either a CH or Cluster Member (CM). The BS is assumed to have unlimited resources. The locations of the BS and SNs are fixed, and the distance between SNs is calculated using the Received Signal Strength Indicator [23]. The channels are assumed to be ideal as a theoretical assumption (no noise and there will be no information loss during data transmission) [24].

B. Energy Model

The radio energy model for an SN follows the first-order radio model. All SNs have two types of transmitting amplifier powers: one for long distances and another for short distances [25]. E_{TX} is the energy required to transmit k bits over a distance d. E_{RX} is the energy expended to receive k bits. E_{TX} and E_{RX} are calculated by:

$$E_{TX}\begin{cases} k.E_{elec} + kE_{fs}.d^2, d < d_0 \\ k.E_{elec} + kE_{mp}.d^4, d \geq d_0 \end{cases} \quad (1)$$

$$E_{RX}(k) = k.E_{elec} \quad (2)$$

Where E_{elec} represents the energy consumed by the transmitter or receiver circuitry to send or receive one bit. E_{fs} is the coefficient for the free-space channel model with d^2 power loss, and E_{mp} is the coefficient for the multipath fading channel model with d^4 power loss, depending on the distance d_0, calculated by:

$$d_0 = \sqrt{E_{fs}/E_{mp}} \quad (3)$$

TABLE I. COMPARISON BETWEEN DEECRP-DRL AND DIFFERENT CLUSTERING ROUTING ALGORITHMS IN WSNS

Protocol	Year	Deployment	CH election metrics: ER: energy residual D: distance, N: node degree	Clustering process	Hot spot problem	Frequency clustering process	Node type	Routing	Tools
LEACH	2000	Random	Probabilistic	Distributed	-	Each round	Homogeneous	Single-hop	Matlab
HEED	2004	Random	Adaptive (ER, N)	Distributed	Not solved	Each round	Homogeneous	Multi-hop	-
SEP	2004	Random	Probabilistic	Distributed	-	Each round	Heterogeneous	Single-hop	-
DEEC	2017	Random	Adaptive(ER,N)	Distributed	-	Each round	Homogeneous	Single-hop	-
LEACH–EP	2018	Random	Probabilistic	Distributed	-	Static round	Homogeneous	Single-hop	OMNet++
DCAGBS	2020	Random	Adaptive (ER, N)	Hybrid	Not solved	Dynamic round	Homogeneous	Single-hop	Matlab
OPOC	2021	Random	Energy prediction	Centralized	-	Dynamic round	Homogeneous	Single-hop	Matlab NS3
PSO-ACO	2023	Random	Adaptive (Er, D intra-cluster, D inter-cluster, degree)	Centralized	Not solved	Static round	Homogeneous	Multi-hop	Matlab
DEECRP–DRL	2025	Hybrid	Adaptive (ER, D intra-cluster, D inter-cluster)	Distributed	Solved	Dynamic round	Heterogeneous	Multi-hop	OMNet++

III. PROPOSED APPROACH

This section details the proposed DEECRP-DRL protocol, in which SNs are heterogeneous in terms of energy and are organized into two energy levels. The first level is assigned to SNs with an initial energy of E_0; these SNs are referred to as *Normal Nodes* (NNs). The second level is assigned to m percent of SNs that have more initial energy than the NNs; these SNs are known as *Advanced Nodes* (ANs). Depending on their type, NNs are deployed randomly, while ANs are deterministically deployed according to a grid deployment scheme [26]. As in any dynamic clustering routing protocol, the proposed protocol operates in several rounds, with each round representing a time interval consisting of three phases: initialization, setup, and steady-state, as can be seen in the workflow illustrated in Figure 1. The round length is dynamically adjusted based on the estimation and comparison of the remaining residual energy (E_r) of the CHs with a threshold, denoted as $E_{threshold}$, which is calculated based on (13). In the DEECRP-DRL protocol, the number of frames per round differs from those used in the clustering routing protocols [20, 21], where the round duration is calculated offline by the BS [21], and the BS sends the round length value three times throughout the network lifetime [20]. When designing a clustering routing protocol for WSNs, multiple factors need to be considered simultaneously. This kind of multi-factor evaluation problem can be effectively addressed using multi-objective fitness functions [24]. For this reason, two fitness functions are utilized in the proposed approach. One is the Clustering Fitness Function, denoted as as FF_c, used to elect the best CHs. The second is the Routing Fitness Function, denoted as FF_r, used in routing to select the best relay nodes.

A. *Initialization Phase*

In the first round, the BS broadcasts the InitMessage to start the execution of the process. Each NN or AN receives the InitMessage and calculates the approximate distance from the BS, denoted as DistBS, using the RSSI. Each AN that receives this message is considered a CH candidate, denoted as CHc. The CH candidates compete to become the final CHs. To do so, a message, denoted as CHcMsg(Er,DistBS), is broadcast by the CH candidates. Starting from the second round, each CH decides whether to complete the current round or proceed to a new one, depending on a comparison between its residual energy E_r and the threshold $E_{threshold}$. Each SN (both AN and NN) receiving the InitMessage calculates the distances to its neighbors, denoted as $Dist_{i,toj}$ and then broadcasts a CHcMsg(E_r,$Dist_{BS}$) message. The idea is to initially run the clustering process based on a competition among ANs. Over several rounds, the ANs will have residual energy equal to or less than that of the NNs. Therefore, the CHs will dynamically switch between ANs and NNs according to the FF_c function.

B. *The Setup Phase*

This study's proposal aims to conserve the energy consumption of SNs and prolong the network lifetime through the following mechanisms: CHs are elected dynamically without requiring any global information about the network topology, based on the *FFc* function. The control overhead resulting from the periodic CH election process is minimized. SNs schedule the wake-up states, and thus TDMA-slot packets are reduced. CHs are distributed within unequal clusters [27].

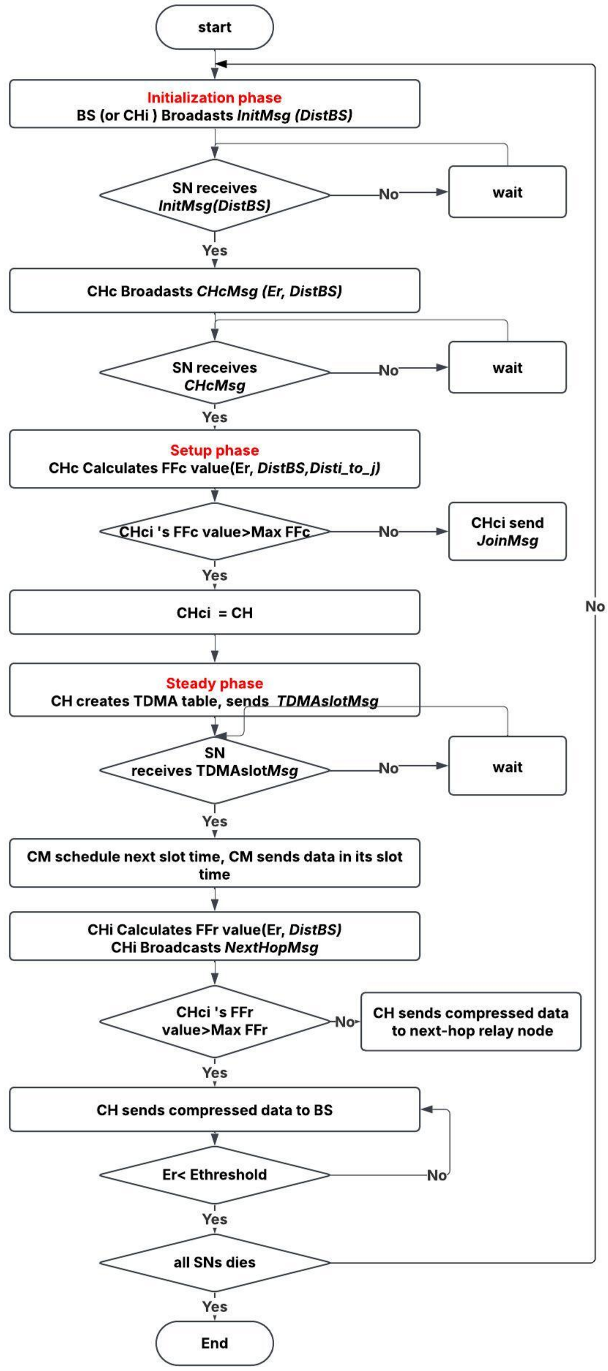

Fig. 1. Flowchart of DEECRP-DRL

- **Step 1:** Each SN_i, having received a CHcMsg(E_r,$Dist_{BS}$) message from a neighboring SN_j, calculates the approximate distance between them, denoted as $Dist_{itoj}$. It then creates a table of CH candidates.
- **Step 2:** Each SN_i calculates the FF_c value for each neighbor SN_j in its table of CH candidates. To do so, the current work denotes by $S=\{CHc_1, CHc_2, \dots, CHc_n\}$ the set of all CH candidates in the system. Each $CHc_i \in S$ can communicate with a subset of neighbors, which are referred to as $N_i = \{CHc_{ij}\} \subseteq S$. The value of the function FF_c depends on three criteria: *residual energy*, the *distance from the BS*, and *the distance from neighbors*. For any given $CH_{ij} \in N_{i=1..k}$, these criteria are represented by the vector $q(CH_{ij}) = [E_r(CH_{ij}), Dist_{BS}(CH_{ij}), Dist_{i\_to\_j}(CH_{ij})]$.The function FF_c aims to determine for each SN_i the best CH $x_i \in Ni$ by maximizing functions f_1 and f_2 and minimizing function f_3, as given in:

$$f_1(x_i) = \max_{CH_{ij} \in N_i} E_r(CH_{ij}) \quad (4)$$

$$f_2(x_i) = \max_{CH_{ij} \in N_i} Dist_{BS}(CH_{ij}) \quad (5)$$

$$f_3(x_i) = \min_{CH_{ij} \in N_i} Dist_{i\_to\_j}(CH_{ij}) \quad (6)$$

Obviously, to determine the value of FF_c , three orthogonal parameters must be optimized simultaneously (i.e., maximization and minimization). To solve this, the present study relies on simple additive weighting, as shown in (7), where the parameters E_r, $Dist_{BS}$, and $Dist_{i\_to\_j}$ in vector q deal with different measurement units. The goal is to convert vector $q\,(CH_{ij})$ into a single normalized real value:

$$FFc(x_i) = \max_{CH_{ij} \in N_i} (w_1 * p_1(CH_{ij}) + w_2 * p_2(CH_{ij}) + w_3 * p_3(CH_{ij})) \quad (7)$$

where:

$$p_1(CH_{ij}) = E_r(CH_{ij}) / E_0$$

$$p_2(CH_{ij}) = Dist_{BS}(CH_{ij}) / Dist_{\max}$$

$$p3(CH_{ij}) = \lfloor Dist_{\max} - Dist_{i\_to\_j}(CH_{ij}) \rfloor / Dist_{\max}$$

$$w_1 + w_2 + w_3 = 1.$$

where E_0 represents the initial energy and $Dist_{max}$ represents the maximum distance, which is the length of the diagonal of the area. The values for the vector $Vect_1 = (w_1, w_2, w_3)$ are empirically set based on experience, as increasing the importance of one parameter reduces the significance of the others. In its protocol, the present study has adopted the following values: w_1= 0.5, w_2= 0.3, and w_3=0.2.

- **Step 3:** Each SN_i compares its FF_c value. If this value is greater than the maximum FF_c value in its table of CH candidates, it becomes a CH. Otherwise, SN_i sends a message, denoted as JoinMsg, to join the CH with the highest FF_c value.
- **Step 4:** When a CH receives the *JoinMsg* message, it waits for a time period T_{wait} before receiving any further JoinMsg messages. T_{wait} is the maximum round-trip time to the farthest SN from the BS.

C. The Steady Phase

Once the clusters are formed, the CHs adopt a TDMA protocol and send a time schedule to each of their CMs [28]. In the proposed protocol, a transmission time slot is assigned to each CM during which the SNs can send their data packets.

The TDMA-based scheduling mechanism places the SNs into an inactive mode until their allocated time slots, as depicted in Figure 2. Since idle listening consumes nearly the same amount of energy as that it receives [29], it is necessary to schedule the SNs into sleep mode and determine the right time to wake them up in order to effectively save energy during idle periods.

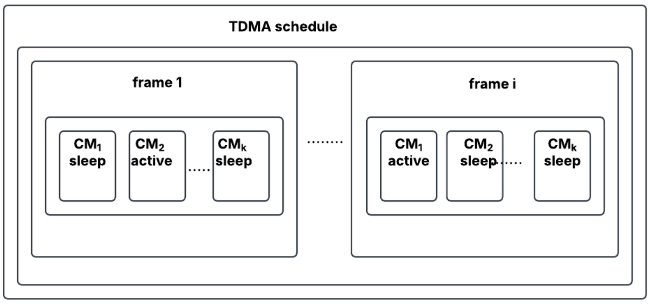

Fig. 2. TDMA schedule visualization.

- **Step 1:** Each CH creates a table of TDMA slots and then sends a message, denoted as *TDMAslotMsg*, to all its CMs, specifying the time slot *T*, its order in the TDMA table, and the size of the table.
- **Step 2:** Each CMi receives the TDMAslotMsg and sends data packets to its CH during its allocated time slot. It then estimates the next slot time based on (8) to schedule its wake-up from sleep mode without needing to receive another TDMAslotMsg message. Unlike most existing protocols, where the CH periodically sends a TDMAslotMsg to wake up sleeping CMs, in the proposed protocol, each CM schedules its states autonomously based on the first TDMAslotMsg:

$$T_{slot} = T_{extra} + O * size * T_{msg} \quad (8)$$

where *O* represents the size, and T_{msg} represents, respectively, the order of CMi in the TDMA table, the size of the TDMA table, and the message's time duration, calculated using:

$$T_{msg} = l / Rb \quad (9)$$

where *l* and *Rb* represent the message length and transmission rate, which is 1 Mbps. Additionally, an extra time, T_{extra}, is added to the expected T_{slot} to avoid the rate of time in transmission; T_{extra} is fixed empirically.

Once the TDMA schedule is established, all CMs send data packets to their CHs during their assigned time slots. The CHs then aggregate the received data. Data aggregation aims to efficiently reduce the number of packets and, consequently, conserve energy [24]. Finally, the CH forwards the aggregated data to the BS in a multihop manner. One of the primary challenges in WSNs is multihop data routing, which involves building an appropriate path between the SN and the BS with low energy consumption for data transmission [30]. For this reason, this study's proposal, instead of calculating all routes from SNs to the BS, it calculates only the next-hop relay nodes based on the FF_r function. Data packets hop from relay node to relay node until they reach the BS [30]. The routing schema in the DEECRP-DRL protocol aims to reduce dynamic routing's energy consumption cost, minimize route distances, ensure a good distribution of relay nodes, and thus prolong the network's lifetime.

- **Step 3:** Each CH_i calculates its *FFr* value based on (12). It then broadcasts a message, denoted as *NextHopMsg*, which includes E_r and $Dist_{BS}$ as parameters.
- **Step 4:** When a given CH_i receives the *NextHopMsg*(E_r, $Dist_{BS}$) message from a neighboring SN_j, it creates a routing table containing its next-hop relay node candidates. This study denotes by $S_{Next\text{-}hop\text{-}relay} = \{CH_1, CH_2\ldots CH_n\}$ the set of all next-hop relay node candidates in the system. Each $CH_i \in S_{Next\text{-}hop\text{-}relay}$ can communicate with a subset of neighbors, referred to as $N_{Next\text{-}hop\ relay\ i} = \{CH_{ij}\} \subseteq S_{Next\text{-}hop\text{-}relay}$. The value of the function *FFr* depends on two criteria: residual energy and the average distance from the BS. For any given $CH_{ij} \in S_{Next\text{-}hop\text{-}relay}$, $i = 1\ldots k$, these criteria are defined as the vector $q_{\text{Next-hop-relay}}(CH_{ij}) = [E_r(CH_{ij}), Dist_{BS}(CH_{ij})]$. The function *FFr* aims to determine the optimal next-hop $x_i \in N_{Next\text{-}hop\ relay\ i}$ for each *CH* by maximizing f_4, while minimizing function f_5 as given in:

$$f_4(x_i) = \max_{CH_{ij} \in N_{Next-hop-relay\ j}} E_r(CH_{ij}) \quad (10)$$

$$f_5(x_i) = \min_{CH_{ij} \in N_{Next-hop-relay\ j}} Dist_{BS}(CHi_j) \quad (11)$$

Likewise, to determine the value of FF_r, two contradictory parameters must be optimized simultaneously. This work relies on simple additive weighting, as shown in (12), to convert the vector $q_{Next\text{-}hop\ \mathrm{relay}(CHij)}$ into a single normalized real value:

$$FFr(x_i) = \max_{CH_{ij} \in N_{Next-hop-relay\ j}} (w_4 * p_4(CH_{ij}) + w_5 * p_5(CH_{ij})) \quad (12)$$

where:

$$p_4(CH_{ij}) = E_r(CH_{ij}) / E_0$$

$$p_5(CH_{ij}) = [Dist_{\max} - Dist_{BS}(CHij)] / Dist_{\max}$$

$$w_4 + w_5 = 1.$$

where E_0 *and* $Dist_{max}$ represent the initial energy and the maximum distance, which equal to the length of the diagonal of Field of Interest (FoI), respectively. The values for vector $Vect_2$ are empirically set based on experience. In the proposed protocol, the following constant values are adopted as scaling parameters: $w_4 = 0.7$ and $w_5 = 0.3$.

Step 5: When the *FFr* value of any given CH_i is greater than all the next-hop CHc in its routing table, it chooses the BS as the next hop and sends data directly. Otherwise, it chooses the CH with the best *FFr* value as the next-hop relay node.

Step 6: If the CH's E_r is less than $E_{threshold}$, it broadcasts a message to declare the end of the current round and start a new one (i.e., broadcasts the *InitMsg*), as displayed in Figure 1. The

$E_{threshold}$ is calculated as given in (13), representing the minimum energy required for a CH to perform one frame:

$$E_{\text{threshold}} = E_{DA} + k * E_{RX} + E_{TX} + E_{relay} \quad (13)$$

where E_{DA} is given in Table I, k represents the number of CMs within a given cluster, and E_{Rx} and E_{Tx} are calculated using (1) and (2), respectively. Finally, E_{relay} represents the energy consumed when receiving data packets from other CHs and retransmitting them to the next hop. E_{relay} is calculated as:

$$E_{relay} = \left| N_{Next-hope-relay} \right| * E_{TX} \quad (14)$$

IV. RESULTS AND DISCUSSIONS

This section thoroughly assesses the performance of the DEECRP-DRL protocol through several simulation experiments. First, the simulation setup details are presented. To validate the proposed approach, parameter values commonly used in relative literature were adopted. Then, the obtained results and the associated discussions were described. The performance of DEECRP-DRL is compared to two protocols: LEACH and LEACH-EP, which represent static and dynamic round-length, and distributed clustering routing protocols, respectively. All experiments are performed using the open-source simulation software platform OMNeT++ 5.0, as it provides effective analysis and modular WSN simulation. The detailed simulation parameters used to obtain the expected results are listed in Table II.

To measure the performance of the proposed protocol, this study relies on experiments grouped into three main scenarios. The aim is to study the impact of the BS location and network scalability (which depends on both network size and density) on energy consumption and, hence, the network lifetime. Each scenario is simulated 30 times, with the locations of SNs changed in each simulation instance. The current work mainly focuses on three aspects: network lifetime, average remaining energy, and the total number of packets received by the BS. For network lifetime, three of the most commonly used metrics in WSNs are deployed: the round at which the *First Node Dies* (FND), the round at which *Half of the Nodes Die* (HND), and the round at which the *Last Node Dies* (LND).

TABLE II. PARAMETERS OF SIMULATIONS

Parameter	Values
Area	(100 m × 100 m) (200 m × 200 m)
Data packet size	4000 bits
Control packet size	512 bits
Number of SNs	$N = 100$; $N = 200$
Initial energy NN	$E_0 = 2$ J
m	5
α	2
BS location	(x,y) = ((100,100) (x,y) = ((150,150)
Distance d0	87 m
E_{elec}	50 nJ/bit
ξ_{fs}	10 pJ/bit/m^2
ξ_{mp}	0.0013 pJ/bit/m^4
E_{DA}	5 nJ/bit/signal

A. First Scenario: Impact of Base Station Location

In this scenario involves three different conditions related to the location of the BS within the Field of Interest (FoI): 1) the BS is located in the center, 2) the BS is located in the left corner and, 3) finally, the BS is located far away. BS location is a critical factor aspect for making comparisons between protocols. Indeed, a given protocol that performs well under certain conditions may perform poorly under others. This study considers 100 NNs randomly distributed in a field of 100 m x 100 m size, according to a uniform distribution for all three protocols.

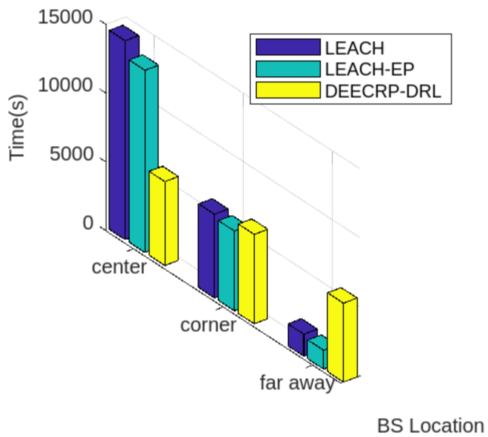

Fig. 3. FDN first scenario.

Figure 3 highlights the impact of BS placement on network performance. LEACH and LEACH-EP perform well with a centrally located BS. However, DEECRP-DRL achieves the highest FND when the BS is at the corner or farther away. This is due to its efficient multi-hop routing, which conserves energy better than direct transmission. Since real-world constraints often prevent optimal BS placement, DEECRP-DRL proves to be a more energy-efficient solution.

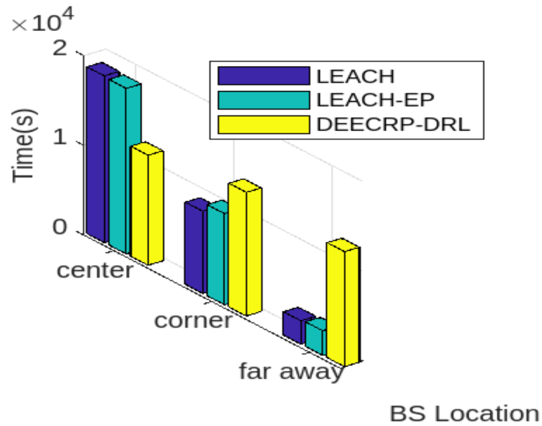

Fig. 4. HDN first scenario.

Figure 4 demonstrates that LEACH and LEACH-EP perform similarly with a centrally located BS, and their HND values drop significantly as the BS moves farther away. In contrast, DEECRP-DRL maintains higher HND values by efficiently managing energy consumption, ensuring a longer network lifespan.

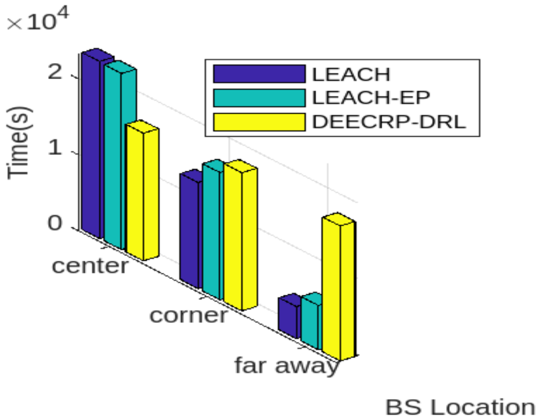

Fig. 5. LDN first scenario.

The bar graph in Figure 5 shows that LEACH and LEACH-EP perform best when the BS is located in the center of the FoI. However, DEECRP-DRL proves to be the most balanced protocol, which achieves the highest LDN value regardless of BS placement. Additionally, although the LDN value in DEECRP-DRL decreases as the BS distance increases, it does so in a more controlled and reasonable manner compared to LEACH and LEACH-EP that demonstrates its superior energy efficiency and resilience. Figure 6 displays the impact of BS placement on energy consumption. LEACH has the lowest remaining energy due to frequent re-clustering in every round, regardless of the residual energy. However, LEACH-EP moderately conserves energy through predictive CH selection. Meanwhile, DEECRP-DRL outperforms both by the use of a multi-criteria CH selection, minimizes overhead, and ensures efficient energy usage, which leads to a prolonged network lifetime.

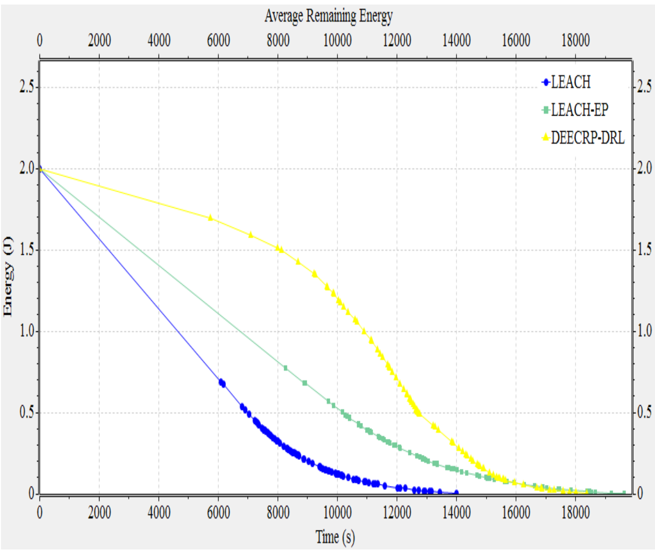

Fig. 6. Average remaining energy for BS in the left corner.

Figure 7 further reinforces these findings. It illustrates the impact of an increased BS distance on energy consumption. LEACH and LEACH-EP experience significant energy depletion as CHs transmit over longer distances.

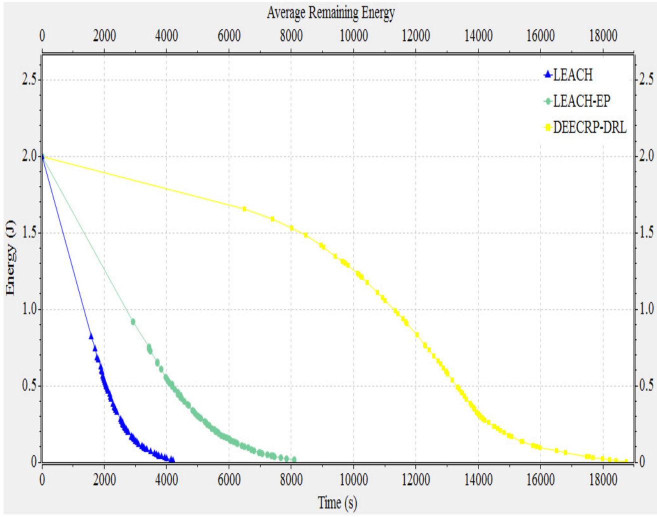

Fig. 7. Average remaining energy for BS far away.

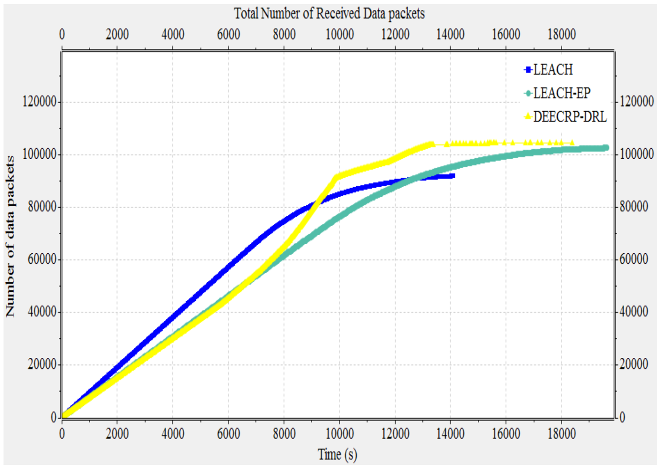

Fig. 8. Number of data packets received by BS in the left corner.

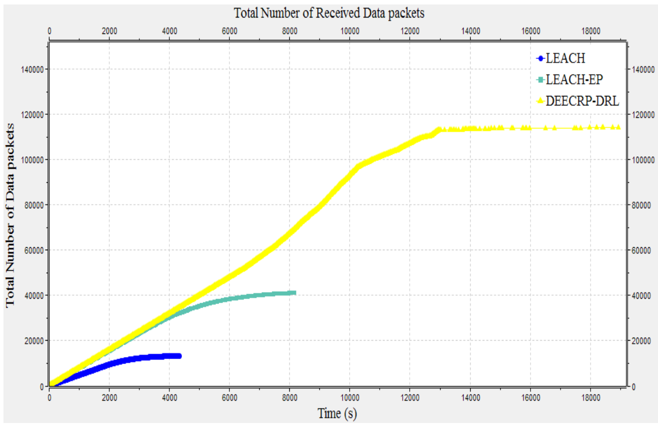

Fig. 9. Number of data packets received by BS far away.

In contrast, DEECRP-DRL optimizes multi-hop inter-cluster communication, which reduces transmission distances and balances energy consumption, making it a more robust and efficient solution especially in scenarios with the challenge of BS placements.

The results illustrated in Figure 8 indicate that when the BS is placed in the corner, it receives approximately the same number of data packets for the DEECRP-DRL and LEACH-EP protocols, because the two protocols perform the clustering process in dynamic rounds. However, in the second case, the number of packets is significantly higher for the DEECRP-DRL protocol, as shown in Figure 9. This is because it prolongs the network lifetime by allowing SNs to conserve their residual energies for much longer, leading to an increase in the number of data packets received by the BS.

B. Second Scenario: Impact of Large Network Area

In this scenario, 100 SNs are dispersed in the same way as in the first scenario. Two test configurations are considered: in the first configuration, the FoI has a size of 100 m x 100 m (a), while in the second configuration, the FoI is 200 m x 200 m (b).

According to Figure 10, the FND values for the three protocols decrease significantly in the second configuration compared to the first one. Moreover, Figure 11 shows that the three protocols delay the HND values by up to 9160 s, 10157 s, and 13853 s for the first configuration, respectively. Similarly, they delay the HND by up to 977 s, 1261 s, and 6430 s for the second configuration, respectively, as evidenced in Figure 12. The DEECRP-DRL protocol has the longest stability period (i.e., the time duration between FND and HND) when compared to the other protocols.

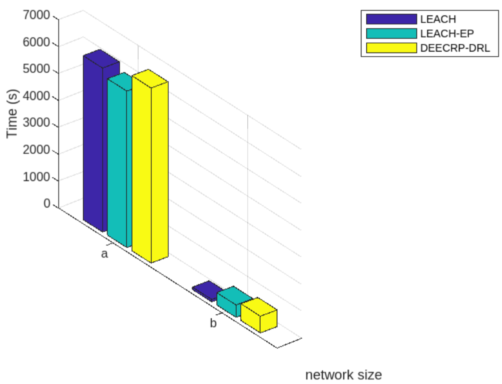

Fig. 10. FDN second scenario.

As displayed in Figure 13, in the first configuration, the three protocols are almost equal in terms of energy dissipation. However, the average remaining energy reveals that DEECRP-DRL is more efficient than LEACH and LEACH-EP in the second configuration, as portrayed in Figure 14. For instance, when LEACH and LEACH-EP consume approximately 50% of the initial energy at times 484 s and 631 s, respectively, DEECRP-DRL dissipates only 28.9% of the total energy. Also, it is observed that all batteries are exhausted in LEACH and LEACH-EP at times 1060 s and 3088 s, respectively, while for DEECRP-DRL, the SNs remain operational with an energy level of 16.3%.

The results illustrated in Figure 15 show that the DEECRP-DRL and LEACH-EP protocols record the highest number of data packets received by the BS. Furthermore, the DEECRP-DRL protocol increases the number of data packets received by up to 1472% and 577.6%, respectively, over LEACH and LEACH-EP, as exhibited in Figure 16.

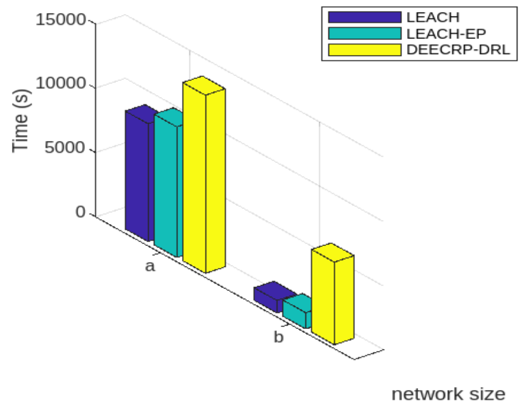

Fig. 11. HDN second scenario.

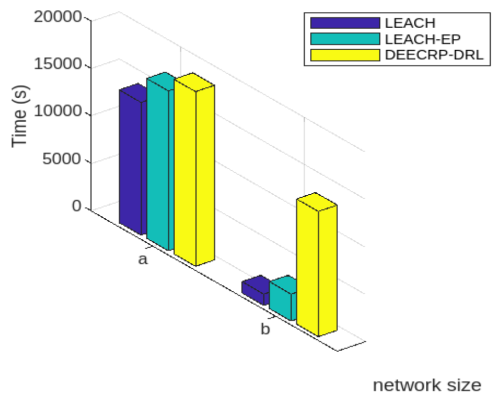

Fig. 12. LDN second scenario.

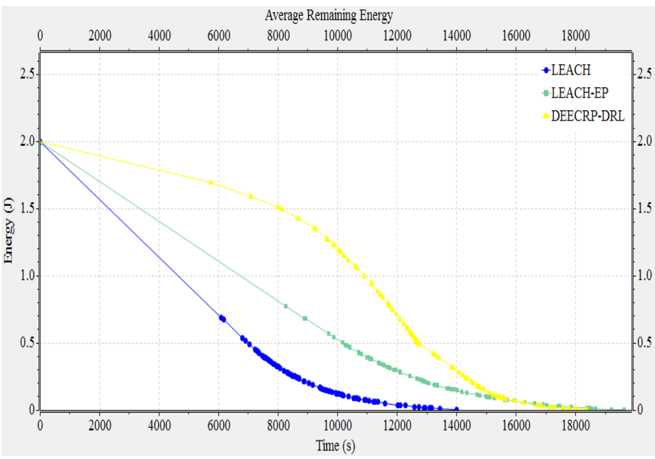

Fig. 13. Average remaining energy network of 100^2 m^2 size.

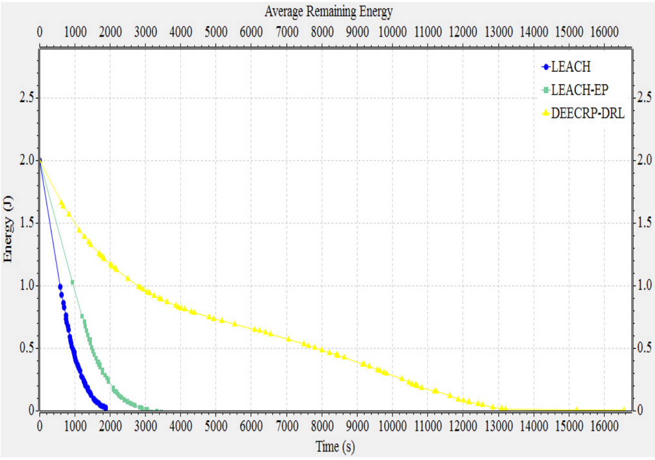

Fig. 14. Average remaining energy network of 200^2 m^2 size.

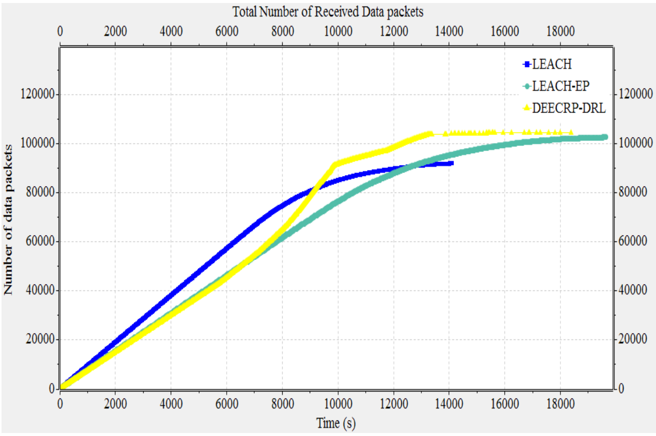

Fig. 15. Number of Received Data packets of network size 100^2 m^2.

C. *Third Scenario: Impact of Network Density*

This scenario examines the impact of network density (i.e., the number of SNs in a given area). The three protocols are simulated by varying the number of SNs in the network area of size 100 m x 100 m from 100 to 200 SNs.

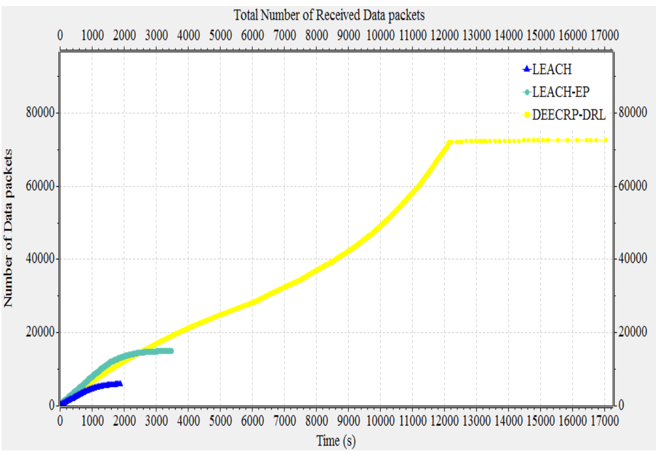

Fig. 16. Number of Received Data packets of network size 200^2 m2.

The results plotted in Figure 17 exhibit that the three protocols are close to each other in terms of FND values at both network densities. However, the DEECRP-DRL protocol outperforms the LEACH and LEACH-EP protocols in terms of HND and LND values for high network density, as demonstrated in Figures 18 and 19.

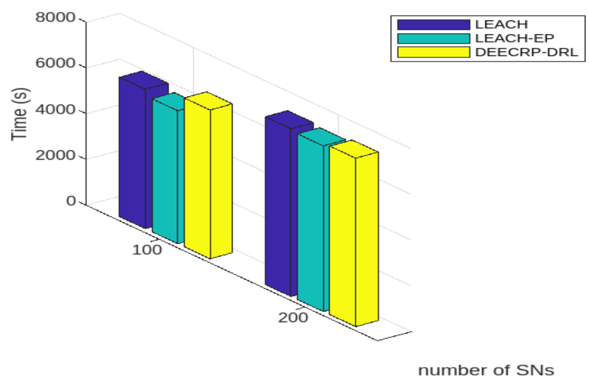

Fig. 17. FDN third scenario.

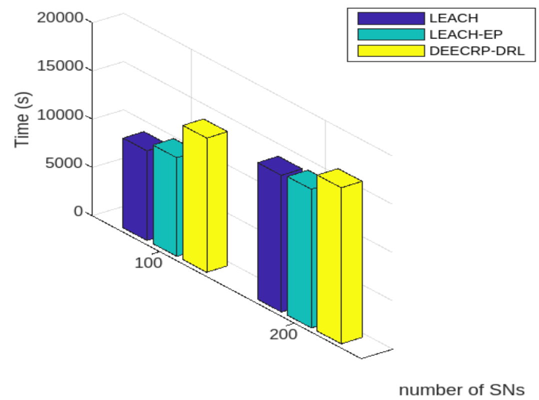

Fig. 18. HDN third scenario.

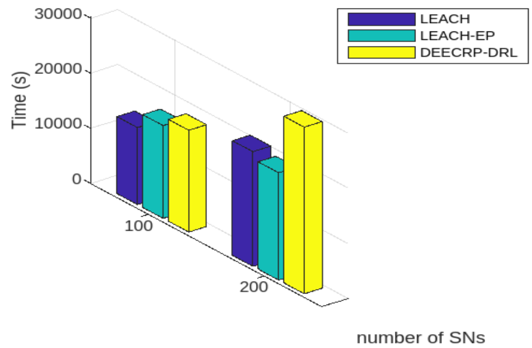

Fig. 19. LDN third scenario.

To confirm the effectiveness of the proposed protocol, the results presented in Figures 20 and 21 depict the performance of the DEECRP-DRL protocol in managing energy more efficiently compared to the LEACH and LEACH-EP protocols at both low and high network densities.

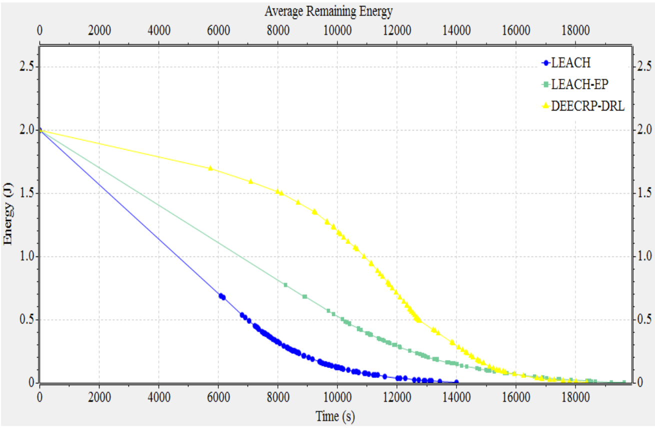

Fig. 20. Average Remaining Energy 100 SNs.

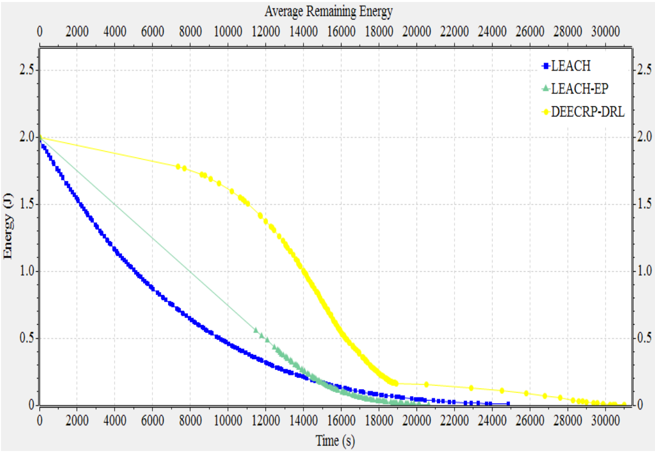

Fig. 21. Average Remaining Energy of 200 SNs.

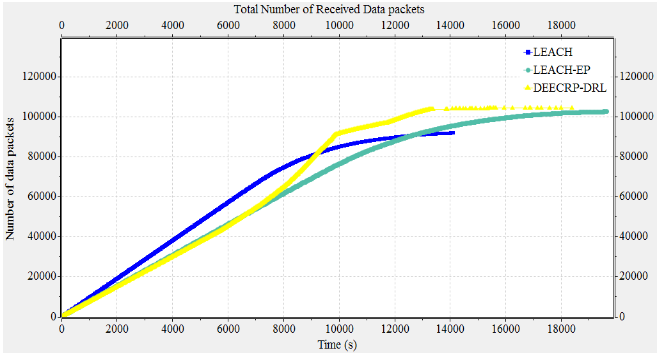

Fig. 22. Total Number of Received Data packets: 100 SNs.

Figure 22 indicates that the number of the data packets received at the BS in the DEECRP-DRL and LEACH-EP protocols is approximately the same at low network density. However, the DEECRP-DRL protocol records a greater number of data packets in high network density, as displayed in Figure 23.

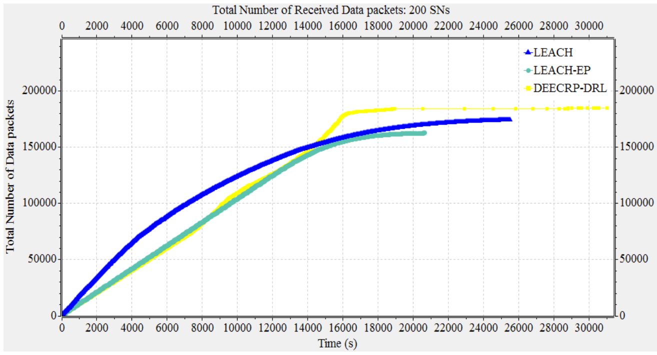

Fig. 23. Total Number of Received Data packets: 200 SNs.

TABLE III. GLOBAL COMPARISON BETWEEN DEECRP-DRL, LEACH, AND LEACH-EP PROTOCOLS

	Complexity	**BS at the left corner**	**BS far away**	**Short area dimensions**	**Large area dimensions**	**Low network density**	**High network density**
LEACH	O(N)	Performs well	Performs poorly	Performs well	Performs very poorly	Performs well	Performs well
LEACH-EP	O(N log N	Performs well	Performs poorly	Performs very well	Performs poorly	Performs very well	Performs well
DEECRP-DRL	O(N log N)	Performs very well	Performs very well	Performs very well	Performs very well	Performs very well	Performs very well

V. DEECRP-DRL PROTOCOL ASSESSMENT AGAINST LEACH AND LEACH-EP PROTOCOLS

Building on the previous discussion, Table III summarizes a global comparison of the performances of DEECRP-DRL, LEACH, and LEACH-EP. In summary, the results indicate that the proposed DEECRP-DRL protocol effectively extends network lifetime and relatively distributes energy consumption among SNs. Table III demonstrates that LEACH is the simplest (O(N)), but lacks energy-efficient CH selection. LEACH-EP incorporates energy prediction, which makes CH selection more complex (O(N log N)). DEECRP-DRL has a similar complexity to LEACH-EP (O(N log N)).

Table III indicates that the three protocols perform well when the BS is positioned in the left corner of the FoI, efficiently managing energy and extending the network's lifetime. The proximity of the BS to the FoI reduces the average distance from CHs, conserving energy. However, deploying the BS near the FoI can be challenging due to factors, like hostile zones and lack of power sources. In other scenarios, the performance of the LEACH and LEACH-EP protocols decreases significantly. CH election based on probabilities can result in SNs with low energy or inappropriate locations being selected as CHs [8], leading to quick CH death and coverage issues [31]. Additionally, the frequent re-clustering in iterative LEACH protocols introduces high overhead, reducing network lifetime due to increased energy consumption [30]. The need for CHs to periodically send TDMA slot packets to CMs further drains energy, as does the reception of these packets. Furthermore, the energy consumption in SNs is mainly affected by data transmission, which increases exponentially with distance, making single-hop inter-cluster communication unsuitable for large-scale WSNs.

Indeed, each CH must periodically send TDMA slot packets to all their CMs, which must intercept them to update their next slot. Consequently, the retransmission of TDMA slot packets by the CH consumes considerable energy, as does the reception of TDMA packets by the CMs [28]. Furthermore, single-hop data transmission shows poor results for large-scale WSNs because the energy is exponentially affected by the distance.

Table III shows that the DEECRP-DRL protocol outperforms the LEACH and LEACH-EP protocols in all scenarios. This is due to its effective management of energy consumption during both the clustering and routing phases. The deterministic deployment of ANs ensures practical application design and the effectiveness of the WSN. The distributed clustering process reduces the overhead caused by information exchange, while adaptive CH election balances the load across SNs. Moreover, adaptive clustering based on residual energy and distance selects the optimal set of CHs, and dynamic round length minimizes re-clustering overhead [32]. CMs autonomously schedule slot times, reducing TDMA packet transmission. Multi-hop data transmission helps balance energy consumption across different regions. Finally, using a routing table with next-hop relay nodes and forming unequal clusters ensures more efficient energy management and extends the network's lifetime.

VI. CONCLUSION AND FUTURE WORKS

This paper introduces the Distributed Energy-Efficient Clustering Routing Protocol with Dynamic Round Length (DEECRP-DRL) for Wireless Sensor Networks (WSNs). The proposed protocol optimizes both the Cluster Head (CH) election process and the data routing mechanism, thereby extending the network lifetime. Sensor Nodes (SNs) are organized into unequal-sized clusters and dynamically elect the most suitable CHs based on residual energy, intra-cluster distance, and inter-cluster distance. An adaptive Routing Fitness Function (FFr) selects the optimal next-hop relay node to forward data from SNs to the Base Station (BS) via multi-hop transmission. DEECRP-DRL dynamically adapts the round length based on residual energy levels. This mechanism significantly reduces re-clustering overhead, improves energy efficiency, and prolongs network lifetime. Simulation results demonstrate that DEECRP-DRL outperforms LEACH and LEACH-EP in terms of energy efficiency and network lifetime.

Future research will focus on fault-tolerant metrics, mobile SNs, and multi-BS environments to further enhance network scalability and applicability in real-world WSN deployments.

REFERENCES

[1] H. R. H. Al Dallal, "Clustering protocols for energy efficiency analysis in WSNs and the IoT", *Problems of Information Society*, vol. 15, no. 1, pp. 18–24, Feb. 2024. http://doi.org/10.25045/jpis.v15.i1.03.

[2] I. Daanoune, B. Abdennaceur, and A. Ballouk, "A comprehensive survey on LEACH-based clustering routing protocols in Wireless Sensor Networks," *Ad Hoc Networks*, vol. 114, Apr. 2021, Art. no. 102409 https://doi.org/10.1016/j.adhoc.2020.102409.

[3] P. Kaur, K. Kaur, D. K. Verma, K. Singh, K. Kaushik, and V. Singh, "Routing Protocols in Wireless Sensor Networks: A Comprehensive Review and Future Perspectives," in *2024 7th International Conference on Contemporary Computing and Informatics (IC3I)*, Sep. 2024, vol. 7, pp. 263–270, https://doi.org/10.1109/IC3I61595.2024.10828894.

[4] Q. Huamei, L. Chubin, G. Yijiahe, X. Wangping, and J. Ying, "An energy-efficient non-uniform clustering routing protocol based on improved shuffled frog leaping algorithm for wireless sensor networks," *IET Communications*, vol. 15, no. 3, pp. 374–383, 2021, https://doi.org/10.1049/cmu2.12067.

[5] N. Temene, C. Sergiou, C. Georgiou, and V. Vassiliou, "A Survey on Mobility in Wireless Sensor Networks," *Ad Hoc Networks*, vol. 125, p. 102726, Feb. 2022, Art. no. 102726, https://doi.org/10.1016/j.adhoc.2021.102726.

[6] H. M. A. Fahmy, "WSN Applications," in *Concepts, Applications, Experimentation and Analysis of Wireless Sensor Networks*, 2nd ed., Cham, Switzerland: Springer, Nov. 2020, pp. 67–232, https://doi.org/10.1007/978-3-030-58015-5_3.

[7] S. Panbude, B. Iyer, A. B. Nandgaonkar, and P. S. Deshpande, "DFPC: Dynamic Fuzzy-based Primary User Aware clustering for Cognitive Radio Wireless Sensor Networks," *Engineering, Technology & Applied Science Research*, vol. 13, no. 6, pp. 12058–12067, Dec. 2023, https://doi.org/10.48084/etasr.6279.

[8] D. W. Wajgi and J. V. Tembhurne, "Localization in wireless sensor networks and wireless multimedia sensor networks using clustering techniques," *Multimedia Tools and Applications*, vol. 83, no. 3, pp. 6829–6879, Jan. 2024, https://doi.org/10.1007/s11042-023-15956-z.

[9] W. Zhou, "Research on Wireless Sensor Network Access Control and Load Balancing in the Industrial Digital Twin Scenario," *Journal of Sensors*, vol. 2022, Jan 2022, Art. no. 3929958, https://doi.org/10.1155/2022/3929958.

[10] N. Kumar, P. Rani, V. Kumar, S. V. Athawale, and D. Koundal, "EEECA-THWSN: Enhanced energy-efficient clustering approach for three-tier heterogeneous wireless sensor networks," *IEEE Sensors Journal*, vol. 22, no. 20, pp. 20053–20062, Oct. 2022, https://doi.org/10.1109/JSEN.2022.3200597.

[11] V. K. H. Prasad and S. Periyasamy, "Energy optimisation-based clustering protocols in wireless sensor networks and internet of things - survey," *International Journal of Distributed Sensor Networks*, vol. 2023, Jan 2023, Art. no. 1362417, https://doi.org/10.1155/2023/1362417.

[12] X. Cao, L. Liu, Y. Cheng, and X. Shen, "Towards Energy-Efficient Wireless Networking in the Big Data Era: A Survey, " *IEEE Communications Surveys & Tutorials*, vol. 20, no. 1, pp. 303–332, 2018, https://doi.org/10.1109/COMST.2017.2771534.

[13] R. Sharma, V. Vashisht, A. V. Singh, and S. Kumar, "Analysis of Existing Clustering Algorithms for Wireless Sensor Networks," in *System Performance and Management Analytics*, P. K. Kapur, Y. Klochkov, A. K. Verma, and G. Singh, Eds. Singapore: Springer Singapore, 2019, pp. 259–277, https://doi.org/10.1007/978-981-10-7323-6_22.

[14] N. Merabtine, D. Djenouri, and D.-E. Zegour, "Towards energy efficient clustering in wireless sensor networks: A comprehensive review," *IEEE Access*, vol. 9, pp. 92688–92705, 2021, https://doi.org/10.1109/ACCESS.2021.3092509.

[15] W. R. Heinzelman, A. Chandrakasan and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences*, Maui, HI, USA, 2000, pp. 10 pp. vol.2-, doi: 10.1109/HICSS.2000.926982.

[16] L. Wu, L. Nie, B. Liu, J. Cui, and N. Xiong, "An energy-balanced cluster head selection method for clustering routing in WSN," *Journal of Internet Technology*, vol. 19, no. 1, pp. 115–125, Jan. 2018, [Online] Available: https://jit.ndhu.edu.tw/article/view/183.

[17] O. Younis and S. Fahmy, "HEED: A Hybrid, Energy-Efficient, Distributed Clustering Approach for Ad Hoc Sensor Networks," *IEEE Transactions on Mobile Computing*, vol. 3, no. 4, pp. 366–379, Oct.–Dec. 2004, https://doi.org/10.1109/TMC.2004.41.

[18] G. Smaragdakis, I. Matta, and A. Bestavros, "SEP: A Stable Election Protocol for clustered heterogeneous wireless sensor networks," *Second International Workshop on Sensor and Actor Network Protocols and Applications (SANPA 2004)*, Boston, MA, USA, Aug. 2004, [Online] Available: https://csr.bu.edu/sep/.

[19] S. Singh, A. Malik, and R. Kumar, "Energy efficient heterogeneous DEEC protocol for enhancing lifetime in WSNs," *Engineering Science and Technology, an International Journal*, vol. 20, no. 1, pp. 345–353, Feb. 2017, https://doi.org/10.1016/j.jestch.2016.08.009

[20] A.-J. Yuste-Delgado, J.-C. Cuevas-Martinez, and A. Triviño-Cabrera, "A distributed clustering algorithm guided by the base station to extend the lifetime of wireless sensor networks," *Sensors*, vol. 20, no. 8, Apr. 2020, Art. no. 2312, https://doi.org/10.3390/s20082312.

[21] N. Merabtine, D. Djenouri, D. E. Zegour, A. Bounnssairi, and K. Rahmani, "Towards optimized one-step clustering approach in wireless sensor networks," *Wireless Personal Communications*, vol. 120, no. 2, pp. 1501–1523, May 2021, https://doi.org/10.1007/s11277-021-08521-0.

[22] S. Soundararajan, C. Kurangi, A. Basha, J. Uthayakumar, K. Kalaivani, M. Dhamodaran, and N. K. Shukla, "Metaheuristic Optimization Based Node Localization and Multihop Routing Scheme with Mobile Sink for Wireless Sensor Networks," *Wireless Personal Communications*, vol. 129, no. 4, pp. 2583–2605, Apr. 2023, https://doi.org/10.1007/s11277-023-10247-0.

[23] M. Omari, M. Kaddi, K. Salameh, A. Alnoman, K. Elfatmi, and F. Baarab, "Enhancing Node Localization Accuracy in Wireless Sensor Networks: A Hybrid Approach Leveraging Bounding Box and Harmony Search," *IEEE Access*, vol. 12, pp. 86752–86781, 2024, https://doi.org/10.1109/ACCESS.2024.3417227.

[24] V. Ranjan, Harsh, D. R. Sharma, and A. K. Arunesh, "Fuzzy based Energy Efficient Clustering in Homogeneous WSN. " Social Science Research Network, Rochester, NY, May 10, 2024, https://doi.org/10.2139/ssrn.4823881.

[25] Y. S. Miao, C. J. Zhao, and H. R. Wu, "Non-uniform clustering routing protocol of wheat farmland based on effective energy consumption," *International Journal of Agricultural and Biological Engineering*, vol. 14, no. 3, pp. 163–170, May 2021, https://doi.org/10.25165/j.ijabe.20211403.6540.

[26] R. Priyadarshi, B. Gupta, and A. Anurag, "Deployment techniques in wireless sensor networks: A survey, classification, challenges, and future research issues," *Journal of Supercomputing*, vol. 76, no. 9, pp. 7333–7373, Jan. 2020, https://doi.org/10.1007/s11227-020-03166-5.

[27] R. Joon, P. Tomar, G. Kumar, B. Balusamy, and A. Nayyar, "Unequal clustering energy hole avoidance (UCEHA) algorithm in cognitive radio wireless sensor networks (CRWSNs)," *Wireless Networks*, vol. 31, pp. 735–757, 2024, https://doi.org/10.1007/s11276-024-03801-6.

[28] A. Bhatia and R. C. Hansdah, "A distributed TDMA slot scheduling algorithm for spatially correlated contention in WSNs," *Mobile Information Systems*, vol. 2015, 2015, Art. no. 234143, https://doi.org/10.1155/2015/234143.

[29] M. S. Mutar, Z. A. Hamza, D. A. Hammood, and S. A. A. Hashem, "Survey of sleep scheduling techniques in wireless sensor networks for maximizing energy efficiency," *AIP Conference Proceedings*, vol. 3232, no. 1, Oct. 2024, Art. no. 020058, https://doi.org/10.1063/5.0236138.

[30] S. P. Singh and S. C. Sharma, "A survey on cluster-based routing protocols in wireless sensor networks," *Procedia Computer Science*, vol. 45, pp. 687–695, 2015, https://doi.org/10.1016/j.procs.2015.03.160.

[31] M. Demri, S. Ferouhat, S. Zakaria, and M. E. Barmati, "A hybrid approach for optimal clustering in wireless sensor networks using cuckoo search and simulated annealing algorithms," in *Proceedings of the 2nd International Conference on Mathematics and Information Technology (ICMIT)*, Adrar, Algeria, pp. 202–207, Dec. 2020, https://doi.org/10.1109/ICMIT.2020.9334156.

[32] W. Osamy and A. M. Khedr, "Adaptive and dynamic mechanism for round length determination in cluster-based wireless sensor networks," *Wireless Personal Communications*, vol. 114, no. 2, pp. 1155–1175, May 2020, https://doi.org/10.1007/s11277-020-07413-z.