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MRETDC: Multi-Level Residual Energy Weight Threshold for Dramatic Change Wireless Sensor Networks

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Abstract

In the wireless sensor networks (WSNs) design, the longevity of the network is one of the most vital factors. Since all the sensor nodes that are placed in the sensing area have a limitation in battery lifetime and are usually situated in a distant or hazardous area. Thus, battery replacement is a difficult task to process. An efficient protocol design is important to extend the network lifetime. This paper is an improvement of the existing threshold-sensitive stable election protocol (TSEP) that executes a probability weight on residual energy for the cluster head selection process. In the proposed protocol, the sensor nodes are categorized into four different initial energies called normal, intermediate, advanced, and extreme nodes. The simulation result shows that the proposed protocol has better performance than SEP and TSEP protocols. The improvement in terms of stability period is approximately increased by 170% and 30% in comparison to SEP and TSEP, respectively. The performance in terms of network lifetime is approximately increased by 280% and 20% in comparison to SEP and TSEP, respectively.

Keywords

Wireless Sensor Network, Heterogeneous Network, Clustering, Routing Protocol, Network Lifetime, Energy Efficiency

1. Introduction

Wireless sensor networks (WSNs) are an emerging class of network systems that consist of large numbers of small, autonomous devices, called sensors, which are capable of sensing and gathering data from their surrounding environment [1]. WSNs have gained significant interest in recent years due to their potential to enable a wide range of applications, including environmental monitoring, industrial automation, healthcare, and many more [2, 3]. One of the most important characteristics of WSNs is their ability to operate autonomously and self-organize. Each sensor in the network is typically equipped with a small radio transceiver and a microcontroller, and is responsible for sensing and processing information about its environment, as well as communicating with its neighbors to route data to the appropriate destination [4, 5]. However, a significant constraint of sensor nodes is their limited operating lifespan.

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They are often situated in risky or distant areas, making it difficult or impractical to replace the battery, which ultimately reduces the network's overall lifetime and performance [6]. Addressing this issue, finding efficient methods to preserve energy consumption has become a challenging focus of research in the field of WSNs [7]. In recent times, artificial intelligence (AI) has emerged as a disruptive technology that has the potential to improve the efficiency of the decision-making process and enable the development of more effective algorithms [8]. Recent studies have investigated the application of various AI techniques, including machine learning [9], fuzzy logic [10], neural networks [11], and metaheuristic algorithms [12] to communication networks and routing protocols. These approaches have shown promise in improving the performance and efficiency of these protocols. In particular, the integration of AI techniques has been found to optimize the communication network and routing protocols, making them more reliable and robust.

Depending on the desired application, WSNs can be divided into two scenarios: proactive and reactive. In a proactive network, sensed data is continuously collected from the area of interest and delivered to the base station through the cluster head. This type of network is commonly used for monitoring applications. On the other hand, in a reactive network, sensed data is transmitted to the base station based on user requests or whenever there is a significant change in the focus environment. Nodes in the network respond rapidly to sudden changes in the relevant parameter of interest beyond a predefined threshold value, making them well-suited for critical event applications such as temperature monitoring or military surveillance [13]. In addition to its operational modes, WSN architecture can be categorized into two types: layered network architecture and cluster architecture. The former, known as the OSI architecture model, consists of five basic layers and three additional cross layers [14]. In the latter, sensor nodes are grouped into clusters, with each cluster governed by a leader node, known as the cluster head, as depicted in Fig. 1. The cluster head aggregates and eliminates redundant data before transferring it to the base station (BS) or sink. While the base station is a rechargeable battery node, the normal node is a low-energy node. Once the base station receives the data from the cluster head, it processes and computes the data to provide comprehensible results to the end user, who can access the information through the internet or satellite network. Therefore, clustering algorithms are well-known and effective techniques for energy balancing and reduction [15].

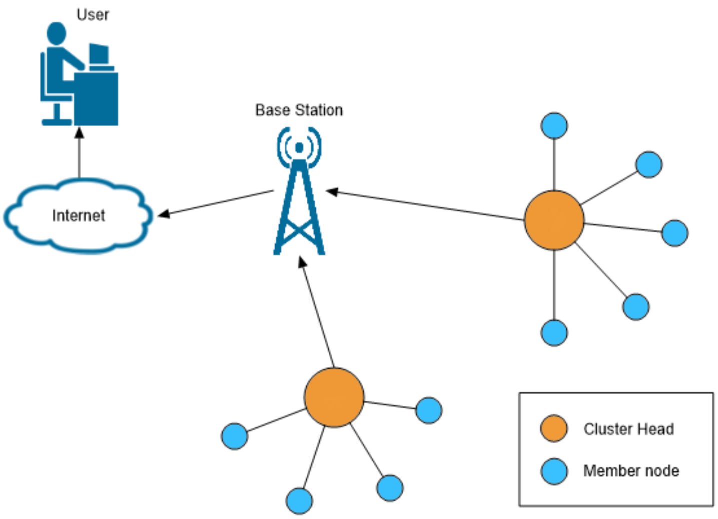


Fig. 1. The cluster architecture in WSNs. In the cluster architecture, sensor nodes are grouped into clusters, with each cluster governed by a leader node, known as the cluster head. The cluster head aggregates and eliminates redundant data before transferring it to the base station. Once the base station receives the data from the cluster head, it processes and computes the data to provide comprehensible results to the end user, who can access the information through the Internet network.

The primary advantage of employing clustering techniques is the reduction of energy consumption in the network by minimizing communication overheads [16]. Therefore, the selection process of the cluster head is crucial and must be executed intelligently to improve network performance and extend its lifetime [17, 18]. Furthermore, clustering networks can be categorized into two types: homogeneous and heterogeneous [19]. In homogeneous sensor networks, all sensor nodes possess the same battery energy, connectivity range, and computation capabilities, as illustrated in Fig. 2(a). Conversely, in a heterogeneous network, sensor nodes may possess different initial energy levels or have differing abilities, as depicted in Fig. 2(b) [20]. The low energy adaptive clustering hierarchy (LEACH) protocol was developed as an initial clustering hierarchical protocol that offered energy-efficient advantages for homogeneous WSNs [21, 22]. However, as the need to extend the operating time of WSNs arose, the concept of heterogeneous networks emerged. The stable election protocol (SEP) proposed the idea of equipping nodes with different energy levels, which can extend the network lifetime. This protocol introduces advanced and normal nodes with different initial energy levels, with the advanced node having higher energy than the normal node [23].

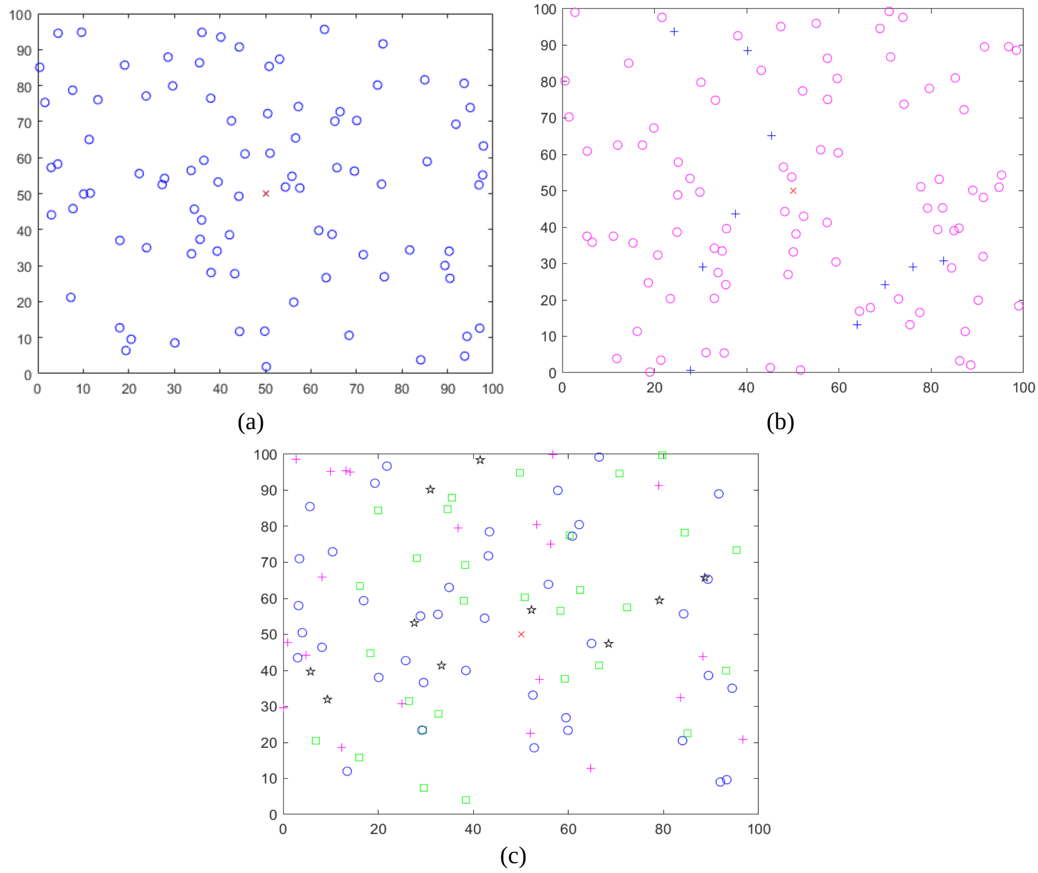


Fig. 2. (a) Homogeneous network, (b) heterogeneous network, and (c) proposed network. The '×' symbol refers to a base station, '◦' symbol refers to the normal nodes, '□' symbol refers to the intermediate nodes, '+' symbol refers to the advanced nodes, and '⋆' symbol refers to the extreme nodes.

As a result, heterogeneous WSN architectures are receiving increased attention from researchers because they can improve network performance without incurring additional costs [24, 25]. The threshold-sensitive stable election protocol (TSEP) protocol was later proposed for a reactive network to improve the network performance by combining favorable aspects of previous protocols such as LEACH [22], SEP [23], ESEP [26], and TEEN [13]. This paper focuses on the reactive network architecture inspired by TSEP and presents an improved TSEP protocol named MRETDC, designed to enhance network performance in terms of stability and lifetime. MRETDC introduces four types of nodes with varying initial energies, namely normal, intermediate, advanced, and extreme nodes, as depicted in Fig. 2(c). The extreme node holds the highest energy. Based on the evidence presented, it can be inferred that heterogeneous networks are more effective when deployed in WSN applications [27, 28]. In order to improve the network performance of WSNs, this study makes the following contributions:

1) The objective of this work is to enhance the performance of the reactive network by proposing a modified version of the TSEP protocol that introduces four types of nodes, including normal, intermediate, advanced, and extreme nodes.
2) The proposed protocol improves stability period and network lifetime by considering node residual energy and average network energy in the cluster head selection process, leading to a more energy-efficient network.
3) The proposed method employs a threshold-based approach like TSEP to conserve more energy by minimizing the amount of data transmitted. Specifically, nodes only send data when the sensed value meets or exceeds a predetermined threshold, thereby reducing unnecessary communication and power consumption. This approach optimizes the efficiency of the network while ensuring that critical information is still transmitted in a timely manner.
4) In terms of network lifetime and stability period, the proposed protocol demonstrates superior performance compared to existing baseline works.

The remainder of this paper is structured as follows: Section 2 provides a concise overview of related research works. The system model employed in the proposed protocol is presented in Section 3. Section 4 introduces the proposed energy-efficient protocol for heterogeneous wireless sensor networks (HWSNs). The evaluation metrics and corresponding results are presented in Section 5. Lastly, Section 6 provides a conclusion of the work.

2. Related Work

WSNs are networks composed of sensor nodes with limited battery resources, a characteristic that presents a significant challenge for maintaining network lifetime. To address this issue, researchers have proposed a variety of approaches. From a broader perspective, WSN environments can be categorized as homogeneous, where nodes are of similar type and have similar capabilities, or heterogeneous, where nodes can differ in type and capabilities. The LEACH algorithm is a widely recognized and fundamental approach proposed for homogeneous environments in WSNs [22]. LEACH was the first clustering algorithm proposed in the field and has demonstrated its effectiveness in extending the network lifetime as well as being energy-efficient. Its success has been widely acknowledged in the academic literature. A key feature of the LEACH protocol is its use of a probabilistic model to elect cluster heads. Under this model, every node in the network has an equal chance of becoming a cluster head. The LEACH protocol operates in two phases: the setup phase and the steady-state phase. During the setup phase, the protocol forms clusters and selects cluster heads based on a specific probability. In particular, the desired percentage of cluster heads for each round is represented by P_{opt}. In deciding whether to become a cluster head, sensor nodes generate a random number between 0 and 1. If this random number is lower than a specific threshold $T(n)$ the node becomes a cluster head for the current round. Once sensor nodes are chosen as cluster heads in a given round, they will not be selected again as cluster heads during the same epoch. The probability threshold for a node to become a cluster head in each round is determined by a predefined value, typically denoted as:

$$T(n) = \begin{cases} \dfrac{P_{opt}}{1 - P_{opt} \times \left(\mathrm{rmod}\left(\dfrac{1}{P_{opt}}\right)\right)} & n \in G \\ 0 & otherwise, \end{cases} \quad (1)$$

where r is the number of rounds. G is a set of nodes that have not been cluster heads in the last $1/P_{opt}$ rounds. During the steady-state phase, the selected cluster heads broadcast a time division multiple access (TDMA) schedule to the member nodes within their cluster. The member nodes then transmit their sensed data to their respective cluster head using single-hop transmission. Subsequently, the cluster heads aggregate the received data from their member nodes and forward it to the base station [29].

Although the LEACH protocol is designed to reduce energy consumption, it still requires a significant amount of energy to maintain the cluster heads and to transmit data to the sink node. This energy consumption can lead to faster depletion of the sensor nodes' batteries. Moreover, the random selection of cluster heads in LEACH can lead to uneven distribution of workload, with some cluster heads being overloaded while others are idle. This can cause significant network performance degradation and shorten the network lifetime. Several works have been proposed to improve the performance of the LEACH protocol, such as HEED [30], I-LEACH [31], LEACH-C [32], EEACH [33], M-LEACH [34], and MW-LEACH [35]. These works aim to increase network lifetime and surpass the original LEACH protocol. It is important to note, however, that they exclusively address the issue of a homogeneous environment. In an effort to extend the network stability, a number of researchers have sought to address the issue of network lifetime limitations. To tackle this challenge, a SEP was introduced [23]. While the cluster head selection process is similar to LEACH, SEP is specifically tailored for heterogeneous networks by categorizing nodes into two distinct types: advanced nodes and normal nodes. Advanced nodes possess greater energy reserves than their normal counterparts. Furthermore, SEP utilizes a weighted probability-based approach in selecting cluster heads, which favors advanced nodes as candidates. As such, SEP has been shown to offer a longer period of network stability in comparison to LEACH.

Since the advent of the SEP protocol, there has been a heightened interest in heterogeneous networks among researchers due to the belief that these networks can offer superior performance in terms of network longevity. As detailed in [36], the prolong SEP (P-SEP) protocol was introduced as a modification to the traditional SEP protocol. P-SEP, like SEP, considers two levels of node energies, but differs in that all nodes in the network are given an equal opportunity to be selected as cluster heads, provided their energies exceed the threshold value. Additionally, the distance-based clustering protocol (DBCP) was developed to enhance SEP's performance by taking into account the distance between the node and the base station, as discussed in reference [37]. Specifically, nodes will join the cluster headed by the closest cluster head, unless the distance to the base station is shorter, in which case it will transmit data directly to the base station, thus minimizing energy consumption by the node. DEEC [38] and E-DEEC [39] were proposed to enhance the network lifetime and network scalability. E-DEEC introduces a new node type called the super node, which improves network heterogeneity, and incorporates initial and residual energy levels into the cluster head selection process. Results indicate that both protocols outperform traditional SEP. Another protocol, HNBC [40], prioritizes network heterogeneity in its cluster head selection process, taking into account various heterogeneity factor values. In contrast, I-SEP [41] uses a threshold-based method to choose cluster heads for heterogeneous networks. Cluster head nodes are assigned high energy amplification levels, and nodes that revert back to normal nodes in the next round are assigned low energy levels to reduce unnecessary power consumption and avoid cluster and cluster head formation. To address network complexity, ESCVAD [42] uses the Voronoi diagram to deal with the uneven distribution of clusters and sensor nodes, weighting both distance and energy levels in its cluster head election process to achieve balanced energy consumption. Notably, ESCVAD has been shown to reduce signaling interaction frequency when compared to traditional protocols such as LEACH and SEP.

The paper [43] presents ECRP, an energy-efficient cluster-based routing protocol for WSNs. ECRP uses a cost function based on energy and distance factors to minimize and balance energy dissipation during cluster head assignment and data forwarding. ECRP provides an effective and efficient solution for energy-aware clustering and routing in WSNs. A hybrid approach, referred to as the distance aware residual energy-efficient SEP (DARE-SEP), has been proposed for three-level heterogeneous WSNs [44]. In this approach, the residual energy of the node and the distance from the node to the base station are utilized as weights for cluster head selection. The nodes that possess higher energy and are located closer to the base station are given priority. However, the performance of this system has not been extensively evaluated. To address this issue, a cluster-based proactive routing protocol called DE-SEP [45] has been introduced to ensure favorable energy preservation. This protocol takes both energy and distance into account during the cluster head selection process. Moreover, the number of cluster head formations is controlled by defining a limited number of cluster heads, thereby avoiding unnecessary cluster formation and reducing energy waste. In [46], an optimization threshold for cluster head selection is presented. The threshold value is controlled by the level of the three types of node energies, and the distance between the selected cluster heads and the base station is measured to optimize the cluster head selection process.

However, most of the protocols proposed for WSNs are designed for proactive networks. TEEN [28] is an umbrella work for reactive network and aimed at addressing time-critical applications. The TEEN protocol allows users to adjust sensing parameters by assigning threshold values, so that data is transmitted only when the sensor detects a value within the range of interest. This approach reduces the frequency of data transmission and therefore lowers energy consumption in the nodes. Threshold sensitive SEP (TSEP) [47] is a reactive protocol that utilizes three levels of node initial energies and operates in a similar fashion to TEEN, in that data is transmitted only when it exceeds a certain threshold. However, the TSEP protocol has limitations in achieving a balanced distribution of energy consumption, as it does not take into account the residual energy levels of individual nodes. The ETSSEP [48], which is a reactive protocol characterized by three levels of heterogeneity, employs a method that selects cluster heads based on the residual energy level of nodes and the minimum number of clusters per round. In addition, a performance comparison was conducted between ETSSEP and two well-known baseline protocols (SEP and TSEP). Results revealed that ETSSEP outperformed both SEP and TSEP protocols in terms of network stability and lifetime. However, it should be noted that the authors of the study only simulated fixed values of the energy of advance nodes and the number of advance nodes, which may limit the generalizability of the findings. To address this limitation, our proposed protocol incorporates varying values of these parameters to ensure overall performance. Additionally, NSMTSEP [49], introduced in a previous study, also functions as a reactive protocol and incorporates three different values for the node's energy based on neighbor support. To calculate the weight of a node, the label of the node is utilized, and this weight is subsequently used to formulate equations for threshold calculation to select the appropriate cluster head. NSMTSEP has been shown to outperform existing protocols such as LEACH, SEP, TSEP, and ETSSEP. Simulation results indicate that NSMTSEP improves network stability by around 30% compared to TSEP, which is not significantly different from our proposed protocol. However, in terms of network lifetime, NSMTSEP only outperforms TSEP by 3.43%, which is much lower than the approximately six times improvement provided by our proposed protocol. Therefore, we can conclude that our proposed protocol performs better in terms of network lifetime.

To the best of our knowledge, there is currently a lack of research that focuses on reactive networks and proposes heterogeneity of nodes exceeding three levels. To fill this gap, our research aims to enhance the baseline TSEP protocol by incorporating four levels of heterogeneity in node energies and considering the threshold value based on the residual energy of the node and the overall average network energy in the cluster head selection process which can enhance network stability and extend the network lifetime in the heterogeneous network.

3. System Model

3.1 Network Model

Throughout this paper, we consider a scenario where sensor nodes are distributed uniformly and remain stationary within a defined sensing area. Each node possesses equivalent processing and communication range capabilities, and is capable of determining its location and that of its neighbors as well as the base station, by analyzing the signal power received. The nodes are assumed to be in constant operation, sensing and collecting data about their environment. The base station is situated in the center of the network, endowed with unlimited battery power and storage capacity. To optimize data collection and transmission, we propose a hierarchical cluster structure in which cluster head nodes perform data aggregation and transmit the information directly to the base station.

3.2 Radio Energy Dissipation Model

In WSNs, the radio energy dissipation model is an important component for estimating the energy consumption of sensor nodes during communication. This paper uses the fundamental radio energy dissipation model [22] illustrated in Fig. 3. The transmit electronics used to generate and modulate the signal that carries the data to be transmitted over the wireless channel. The power amplifier used to amplify the modulated signal before it is transmitted over the wireless channel, known as the TX amplifier, is a critical component that consumes a significant amount of energy. The receive electronics used to receive and demodulate the signal that carries the data over the wireless channel. This model assumes that the energy dissipation of a sensor node is directly proportional to the distance between the transmitting and receiving nodes and is typically expressed as a power function of the transmission range. In other words, as the distance between the nodes increases, the energy required to transmit a message also increases.

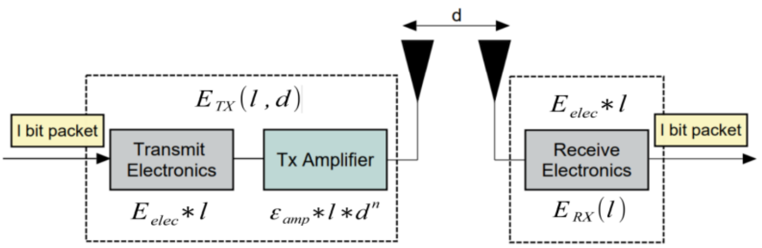


Fig. 3. Radio energy dissipation model. This model is used for estimating the energy consumed by sensor nodes during communication, assuming that energy dissipation is directly proportional to the distance between transmitting and receiving nodes. Energy dissipation increases as the transmission range increases.

The amount of energy that require for transmitting (E_{TX}) and receiving (E_{RX}) l bits data with distance d can be computed as follows:

$$E_{TX}(l,d) = \begin{cases} l \times E_{elec} + l \times \varepsilon_{fs} \times d^2, & d \leq d_0 \\ l \times E_{elec} + l \times \varepsilon_{mp} \times d^4, & d > d_0 \end{cases}, \quad (2)$$

$$E_{RX} = l \times E_{elec}, \quad (3)$$

where E_{elec} denotes the per bit energy dissipation in both transmitter and receiver electronics. l is the number of bits. The distance threshold can be calculated by $d_0 = \sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$. The parameters, ε_{fs} and ε_{mp}, indicate the free space fading model and multipath fading model that are used for the transmitter amplifier, respectively. The choice between using the free space fading model and the multipath fading model is determined by the distance between the transmitter and receiver as shown in Equation (2). If the distance is less than the threshold distance, the free space fading model will be used. Otherwise, the multipath fading model will be used.

3.3 Energy Model

The divergence in node initial energy levels contributes to the heterogeneity of the network. In our proposed protocol, nodes are categorized into four energy levels, with the extreme nodes having the highest initial energy, followed by the advanced nodes. The intermediate nodes have lower energy levels than advanced nodes but higher than normal nodes, while the normal nodes possess the lowest energy level. The network comprises of n randomly distributed nodes, with a fraction m representing the number of advanced nodes. The added energy value between the advanced and normal nodes is denoted by α. Let q and b denote the proportions of nodes that operate as extreme and intermediate nodes, respectively. These nodes are equipped with 3α and μ times the power levels of normal nodes, where μ is set to $\alpha/2$. E_0 represents the exact starting energy of normal nodes, with the initial energy levels of intermediate, advanced, and extreme nodes being $E_0(1+\mu)$, $E_0(1+\alpha)$, and $E_0(1+3\alpha)$, respectively. The energy summarization of each node type is presented below:

$$E_N = nE_0(1-q-m-b), \tag{4}$$

$$E_I = nbE_0(1+\mu), \tag{5}$$

$$E_A = nmE_0(1+\alpha), \tag{6}$$

$$E_E = nqE_0(1+3\alpha), \tag{7}$$

E_N, E_I, E_A, and E_E indicate the overall energy of normal, intermediate, advanced, and extreme nodes, respectively. Hence the total initial energy from every node in the network can be written as:

$$\begin{aligned} E_{total} &= nE_0(1-q-m-b) + nbE_0(1+\mu) + nmE_0(1+\alpha) + nqE_0(1+3\alpha) \\ &= nE_0(1+b\mu+m\alpha+3q\alpha), \end{aligned} \tag{8}$$

In our proposed algorithm, the average energy of the network is needed to know at the beginning of every operating round since it will be calculated in the probability weight function [38]. The average energy of the network at round r is approximated as

$$E_{avg} = \frac{1}{n}E_{total}\left(1-\frac{r}{R}\right), \tag{9}$$

where $\boldsymbol{n}$ is the total number of nodes, $\boldsymbol{E_{total}}$ is the total initial energy of the heterogeneous network, $\boldsymbol{r}$ is the current round and $\boldsymbol{R}$ denotes the total rounds of the network. As mentioned in the network model section, the $\boldsymbol{n}$ sensor nodes are distributed in the interest region $\boldsymbol{M}\times\boldsymbol{M}$ square meters. We assume the base station is located at the middle of the network field and the distance of any node to the base station or its cluster head is less than or equal to $\boldsymbol{d_0}$. Therefore, the energy misspent in the cluster head node in each operating round can be estimated by the following formula:

$$E_{CH} = (\frac{n}{k}-1)l\cdot E_{elec} + \frac{n}{k}l\cdot E_{DA} + l\cdot E_{elec} + l\cdot(\varepsilon_{fs})d_{toBS}^2, \tag{10}$$

where $\boldsymbol{k}$ is the number of clusters, $\boldsymbol{E_{DA}}$ is the energy that is spent in the cluster head nodes during the data aggregation process, and $\boldsymbol{d_{toBS}}$ is the average distance from the cluster head to the base station. The node that has not been selected as a cluster head called a non-cluster head node will spend the energy calculated by

$$E_{non-CH} = l\cdot E_{elec} + l\cdot(\varepsilon_{fs})d_{toCH}^2, \tag{11}$$

where d_{toCH} is the average distance from a non-cluster head node to its cluster head. Therefore, we can estimate the energy used in a cluster per round as:

$$E_{cluster} = E_{CH} + \frac{n}{k}E_{non-CH}. \tag{12}$$

Consequently, the total amount of overall energy spent in the network is equal to:

$$E_{total} = l(2nE_{elec} + nE_{DA} + \varepsilon_{fs}(kd_{toBS}^2 + d_{toCH}^2)). \tag{13}$$

If the nodes are supposed to be uniformly distributed, we can calculate the average distance from a non-cluster head node to its cluster head by:

$$d_{toCH} = \frac{M}{\sqrt{2\pi k}}, \tag{14}$$

and the average distance from a cluster head to the base station:

$$d_{toBS} = 0.765\frac{M}{2}. \tag{15}$$

4. Proposed Algorithm

The proposed MRETDC protocol seeks to enhance the TSEP protocol for critical event applications by leveraging the heterogeneity of node initial energy levels to prolong the network's stability period. The protocol introduces a four-level hierarchy of nodes based on their energy capacities, and employs two threshold values, namely the top and bottom thresholds, to manage data transmission. Specifically, a sensor node continuously monitors the environment within its designated region of interest. When a sensed value surpasses the top threshold, the node activates its transmitter to send the data to the cluster head and stores the most recently sensed value (SV) in its internal memory. The node then resends the data whenever the subsequent sensed value exceeds the top threshold and the difference between the current sensed value and the previously stored value equals or exceeds the bottom threshold. The bottom threshold serves to filter out minor changes in sensed value and reduce unnecessary data transmission. The incorporation of threshold values not only reduces the quantity of data transmission, but also enables a timely and efficient data exchange between nodes and cluster heads. Moreover, the integration of node heterogeneity offers an extended period of network stability. The algorithm of the proposed MRETDC protocol is shown in Algorithm 1.

Algorithm 1. Proposed algorithm

$\boldsymbol{E_{avg}}$:	Average energy of the network
$\boldsymbol{rd}$:	Random number
$\boldsymbol{r}$:	Round number
$\boldsymbol{CH}$:	Cluster head counter
$\boldsymbol{CV}$:	Current sensed value
$\boldsymbol{SV}$:	Sensed value
$\boldsymbol{TT}$:	Top threshold
$\boldsymbol{BT}$:	Bottom threshold
$\boldsymbol{S(i)}$:	Sensor node $\boldsymbol{i}$
$\boldsymbol{E_{s(i)}}$:	Energy of sensor node $\boldsymbol{i}$

```
begin
Deploy sensor nodes in the network;
CH == 0;
Calculate the total initial energy in the network;
for r = 1 to r_max do
    Calculate CV ;
    Calculate E_avg by using Eq. (9);
    if (E_avg > 0) then
        Calculate P_N, P_I , P_A, P_E by using Eq. (16)–(19);
```

```
    for i = 1 to n do
        Calculate T_N, T_I, T_A, T_E; by using Eq. (20)–(23);
        if (E_s(i) > 0 & rd ≤ T_N,I,A,E & G^N,I,A,E > 0) then
          Node S(i) is selected as CH;
          CH = CH + 1;
          if (CV ≥ TT) then
            Calculate the difference between CV and SV;
            if (Diff ≥ BT) then
              Calculate E_TX, E_RX by using Eq. (2)–(3);
              Update E_s(i);
            end if
          end if
        end if
    end for
    for i = 1 to n do
      if (S(i) ∈ Non − CH & E_s(i)) > 0) then
        if (CV ≥ TT) then
          Calculate the difference between CV and SV;
          if (Diff ≥ BT) then
            Calculate E_TX, E_RX by using Eq. (2) – (3);
            Update E_s(i);
          end if
        end if
      end if
    end for
  end if
end for
```

The fundamental method of cluster head election proceeds in the same principle of LEACH and SEP. At the beginning of every round, each node has its own number either 0 or 1. The preliminary energy of each node is equipped with different values depending on its type such as extreme, advanced, intermediate, and normal nodes. Additionally, the average energy of the network and the residual energy of the node are considered in order to achieve the proper cluster heads in each round as in [38, 39]. By considering the remaining energy of the node, the node equipped with higher energy will have more chance to be elected as a cluster head rather than the lower energy node. Therefore, in MRETDC, the extreme nodes are mainly elected as cluster heads as compared to the other nodes. Accordingly, the energy consumption in all nodes is equally distributed. For the characteristic of heterogeneous networks, the nodes are basically possessed different energy in the case of the initial energy. Therefore, extreme nodes, advanced nodes, intermediate nodes as well as normal nodes have an equal chance of evaluation. The weighted probability of each node can derive from Equations (16)–(19), where P_N represents the probability for normal nodes, P_I represents the probability for intermediate nodes, P_A is the probability for advanced nodes and P_E is the probability for extreme nodes.

$$P_N = \frac{P_{opt} \times E_{res}}{(1+b\mu+m\alpha+3q\alpha)\times E_{avg}}, \tag{16}$$

$$P_I = \frac{P_{opt} \times (1+\mu) \times E_{res}}{(1+b\mu+m\alpha+3q\alpha)\times E_{avg}}, \tag{17}$$

$$P_A = \frac{P_{opt} \times (1+\alpha) \times E_{res}}{(1+b\mu+m\alpha+3q\alpha)\times E_{avg}}, \tag{18}$$

$$P_E = \frac{P_{opt} \times (1+3\alpha) \times E_{res}}{(1+b\mu+m\alpha+3q\alpha)\times E_{avg}}. \tag{19}$$

As described in the previous section, the variables q, m and b are the fraction of extreme, advanced and intermediate nodes in the network respectively. The energy of extreme nodes is greater than the other nodes and hold 3α times more power than normal nodes. A parameter α is the additional energy value between advanced and normal nodes. The intermediate nodes have μ times more power than the normal nodes, where $\mu = \alpha/2$. Refer to the traditional protocols, LEACH and SEP, the cluster heads are chosen in each round based on the threshold value. Thus, we substitute P_{opt} by the weighted probabilities of each node in Equation (1) and the chance of each node to become a cluster head in each round are calculated as follows:

$$T_N = \begin{cases} \frac{P_N}{1-P_N \times \left(\text{rmod}\left(\frac{1}{P_N}\right)\right)} & n \in G^N \\ 0 & otherwise \end{cases}, \tag{20}$$

$$T_I = \begin{cases} \frac{P_I}{1-P_I \times \left(\text{rmod}\left(\frac{1}{P_I}\right)\right)} & n \in G^I \\ 0 & otherwise \end{cases}, \tag{21}$$

$$T_A = \begin{cases} \frac{P_A}{1-P_A \times \left(\text{rmod}\left(\frac{1}{P_A}\right)\right)} & n \in G^A \\ 0 & otherwise \end{cases}, \tag{22}$$

$$T_E = \begin{cases} \frac{P_E}{1-P_E \times \left(\text{rmod}\left(\frac{1}{P_E}\right)\right)} & n \in G^E \\ 0 & otherwise \end{cases}. \tag{23}$$

If the random number which is created by each node is less than the threshold value, that node will perform a cluster head role for a current round. From Equations (20)–(23), $\boldsymbol{T_N}$ denotes the threshold for normal nodes, $\boldsymbol{T_I}$ denotes the threshold for intermediate nodes, $\boldsymbol{T_A}$ denotes the threshold for advanced nodes, and $\boldsymbol{T_E}$ denotes the threshold for extreme nodes. Where $\boldsymbol{r}$ is the current round. $\boldsymbol{G^N}$, $\boldsymbol{G^I}$, $\boldsymbol{G^A}$, and $\boldsymbol{G^E}$ are the set of normal, intermediate, advanced, and extreme nodes that have not become cluster heads in the last $\boldsymbol{1/P_N}$, $\boldsymbol{1/P_I}$, $\boldsymbol{1/P_A}$ and $\boldsymbol{1/P_E}$ round, respectively. It indicates that there is no chance for the nodes which are already selected as cluster heads in the same epoch. Now, from Equations (16), (17), (18) and (19), we can obtain the average total cluster heads per round by:

$$n(1 - b - m - q)P_N + nbP_I + nmP_A + nqP_E = nP_{opt}. \tag{24}$$

We can be inferred from the above Equation (24) that the consequence of cluster heads in a heterogeneous network is comparable to result of LEACH protocol. However, the heterogeneous network outperforms in the case of energy dissipation by the diversity of energy levels.

Algorithm 2. The fundamental pseudocode of TSEP and the proposed protocol

$\boldsymbol{T(n)}$:	Threshold
$\boldsymbol{p}$:	The value of the cluster head probability
$\boldsymbol{r}$:	Number of rounds
$\boldsymbol{rd}$:	Random number

```
// Initialization
Create the network topology;
// Rounds
for each round r do
    // Cluster head selection
        for each node i do
          Calculate the value of T(n) = p/(1 − p ∗ (r mod (1/p)))
```

```
Generate a random number (rd) between 0 and 1;
    If rd < T(n) then
        Set i as the cluster head;
        Broadcast the cluster head announcement message;
// Data transmission
    for each non-cluster head node j do
        If j is within the transmission range of a cluster head i and the value of the sensed parameter
        meets or exceeds the pre-configured threshold, then
            Send data to cluster head i;
```

In the data transmission phase, we employ a threshold-sensitive approach similar to that of the TSEP protocol. Specifically, when a non-cluster head node's sensed value reaches the configured threshold, it transmits its data to its cluster head. In Algorithm 2, we present the pseudocode for both the baseline TSEP protocol and our proposed protocol. Both protocols follow the same procedure, but our proposed protocol includes an additional node type called the extreme node, which has a higher energy level than the other node types as described in the previous section. While in TSEP, the protocol only considers three types of nodes. Moreover, we incorporate the average energy of the network and the residual energy of each node into the probability formulation, which helps improve the stability period and network lifetime, as shown in Equations (16)–(19). In contrast, the TSEP protocol does not consider these values when calculating probability.

5. Performance Evaluation

5.1 Simulation Setting

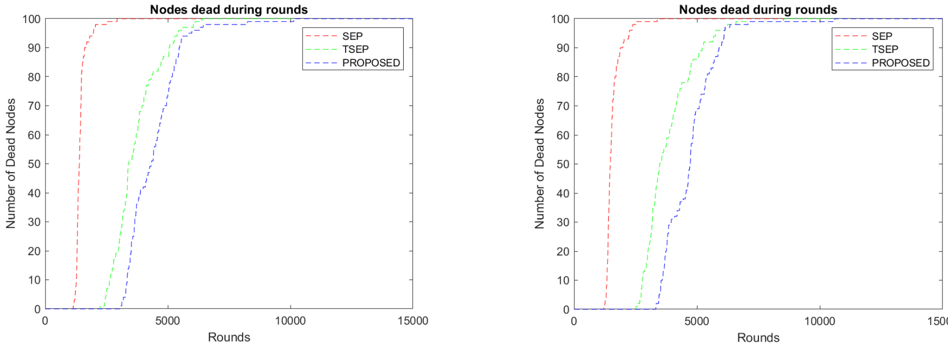
To evaluate the performance of our proposed MRETDC protocol, we conducted simulations using MATLAB. We randomly distributed 100 sensor nodes over a 100×100 square meter network area, with a base station located at the center of the network and having infinite energy. We used the network parameters described in Table 1 to evaluate the stability period, network lifetime, and throughput of our proposed protocol, in comparison to existing baseline protocols, SEP and TSEP, which are also suitable for heterogeneous networks. Our proposed protocol employs four types of nodes, while SEP and TSEP use two and three types of nodes based on the initial energy. Our objective is to reduce node energy consumption and extend network operating time, thereby enhancing network performance. We evaluated the performance of each protocol by varying the value of parameter m, while keeping b constant at 0.3. Here, m and b represent the fractions of advanced and intermediate nodes in the network, respectively. Advanced nodes have a higher energy level than intermediate nodes, making m the variable that has a more significant impact on network performance. Furthermore, all protocols use m as the same variable, representing the fraction of advanced nodes in the network.

Table 1. Network parameters

Parameter	Value
Network size	100 m × 100 m
Number of nodes	100
Initial energy	0.5 J
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
E_{TX} and E_{RX}	50 nJ/bit
E_{DA}	5 nJ/bit
Packet size	4,000 bits

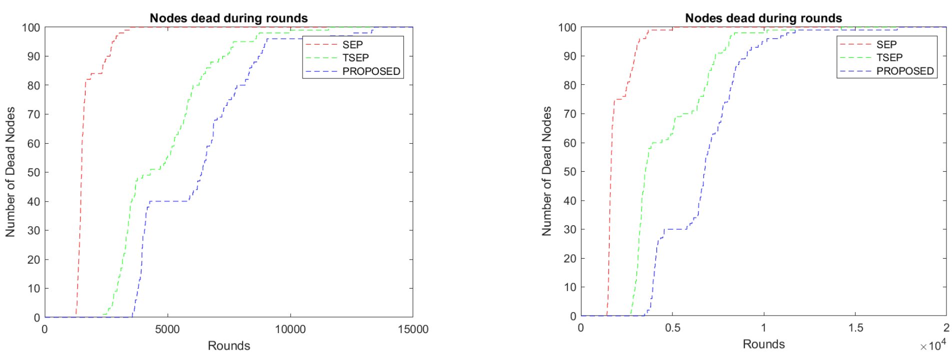
5.2 Performance Comparison

In this section, we present a comparative analysis of our proposed protocol with two baseline protocols, namely SEP and TSEP. The evaluation metrics used for the comparison are stability period, network lifetime, and throughput. The stability period is defined as the duration between the first round of operation and the occurrence of the first node failure. The network lifetime is estimated by observing the period from the first round of operation until the last node failure in the network. Throughput is defined as the number of packets transmitted from the cluster heads to the base station.



(a) (b)

Fig. 4. The comparison of SEP, TSEP, and the proposed protocol with regards to the number of dead nodes versus the number of rounds, for $\alpha = 1$:
(a) $m = 0.2$ and $b = 0.3$ and (b) $m = 0.3$ and $b = 0.3$.

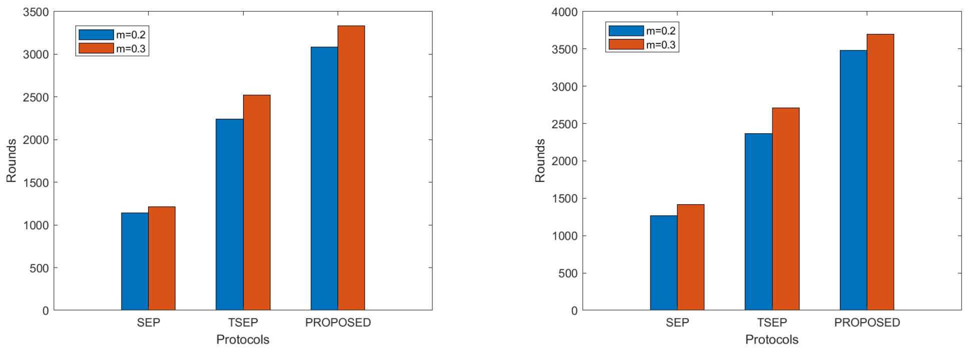


(a) (b)

Fig. 5. The comparison of SEP, TSEP, and the proposed protocol with regards to the number of dead nodes versus the number of rounds, for $\alpha = 2$:
(a) $m = 0.2$ and $b = 0.3$ and (b) $m = 0.3$ and $b = 0.3$.

Figs. 4 and 5 provide a comparison of SEP, TSEP, and the proposed protocol with regards to the number of dead nodes versus the number of rounds, for $\alpha = 1$ and $\alpha = 2$, respectively. The x-axis represents the number of rounds, while the y-axis indicates the number of dead nodes. Each dash line represents a different protocol. The blue dash line represents the proposed protocol, the red dash line represents SEP protocol, and the dash green line represents TSEP protocol. Fig. 4(a) depicts the first node of SEP, TSEP, and the proposed protocol dies at 1,141, 2,242, and 3,084 rounds, respectively for $m = 0.2$ and Fig. 4(b) depicts the first node of SEP, TSEP, and the proposed protocol dies at 1,214, 2,523, and 3,330 rounds, respectively for $m = 0.3$. Fig. 5(a) depicts the first node of SEP, TSEP, and the proposed protocol dies at 1,269, 2,368, and 3,480 rounds, respectively for $m = 0.2$ and Fig. 5(b) depicts the first node of SEP, TSEP, and the proposed protocol dies at 1,417, 2,711, and 3,694 rounds, respectively for $m = 0.3$.

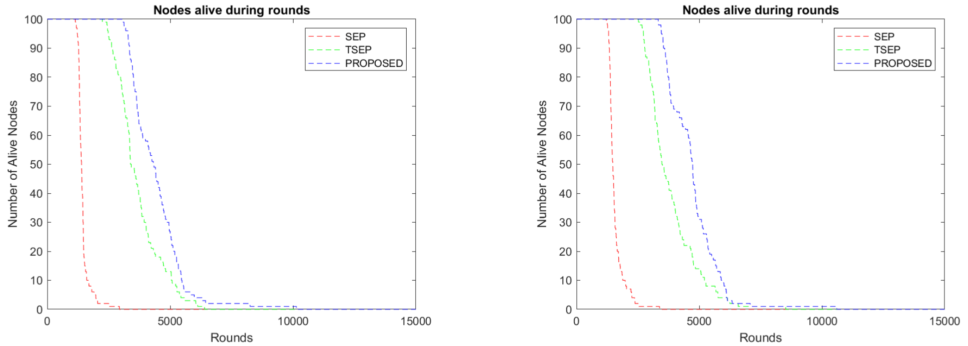
From the results, we compared SEP, TSEP, and the proposed protocol in terms of stability period, for $\boldsymbol{\alpha} = \mathbf{1}$ and $\boldsymbol{\alpha} = \mathbf{2}$, respectively as shown in Fig. 6. The x-axis denotes the different protocols under study, while the y-axis represents the number of rounds. Each bar on the chart corresponds to a varying value of $\boldsymbol{m}$ for each protocol. Our findings indicate that the proposed protocol performs better than both SEP and TSEP, as it exhibits a significantly higher number of rounds before the first node failure during the simulation. Moreover, the results suggest that the proposed protocol offers a more stable network compared to the other two protocols. The proposed MRETDC protocol shows a better result with an approximately increase of 170% and 30% compared to SEP and TSEP, respectively.



(a) (b)

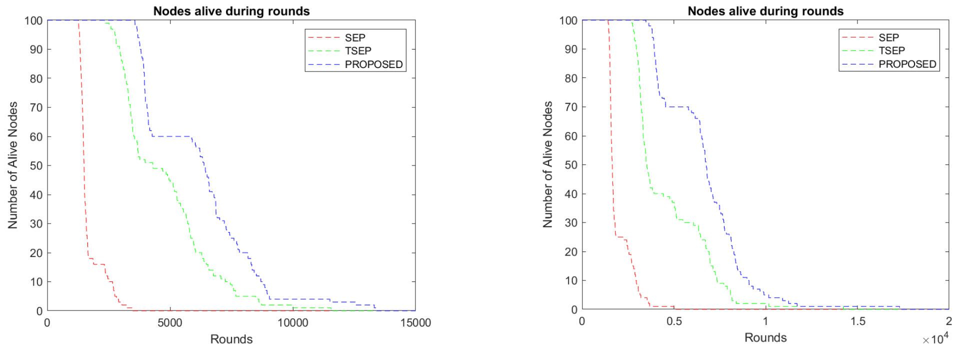
Fig. 6. The comparison of SEP, TSEP, and the proposed protocol in terms of stability period: (a) $\alpha = 1$ and (b) $\alpha = 2$.

In this section, we provide the results of the number of alive nodes versus the number of rounds for SEP, TSEP, and the proposed protocol with α values of 1 and 2, as illustrated in Figs. 7 and 8, respectively. The x-axis represents the number of rounds, while the y-axis indicates the number of alive nodes. Fig. 7(a) depicts the last node of SEP, TSEP, and the proposed protocol dies at 2934, 6401, and 10138 rounds, respectively for $m = 0.2$ and Fig. 7(b) depicts the last node of SEP, TSEP, and the proposed protocol dies at 3,384, 8,525, and 10,604 rounds, respectively for $m = 0.3$. Fig. 8(a) depicts the last node of SEP, TSEP, and the proposed protocol dies at 3,454, 11,554, and 13,413 rounds, respectively for $m = 0.2$. and Fig. 8(b) depicts the last node of SEP, TSEP, and the proposed protocol dies at 5,014, 14,232, and 17,299 rounds, respectively for $m = 0.3$.



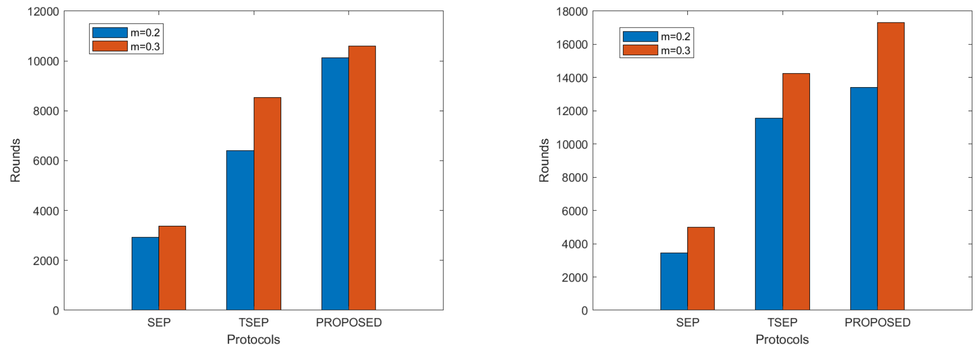
(a) (b)

Fig. 7. The comparison of SEP, TSEP, and the proposed protocol with regards to the number of alive nodes versus the number of rounds, for $\alpha = 1$:
(a) $m = 0.2$ and $b = 0.3$ and (b) $m = 0.3$ and $b = 0.3$.



(a) (b)

Fig. 8. The comparison of SEP, TSEP, and the proposed protocol with regards to the number of alive nodes versus the number of rounds, for $\alpha = 2$:
(a) $m = 0.2$ and $b = 0.3$ and (b) $m = 0.3$ and $b = 0.3$.



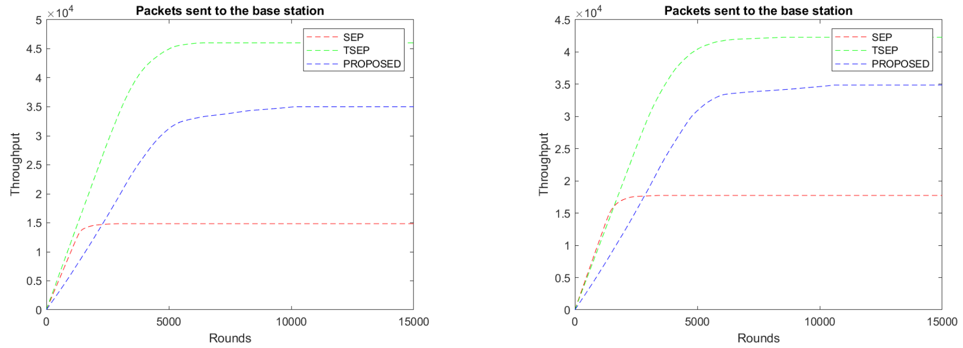
(a) (b)

Fig. 9. The comparison of SEP, TSEP, and the proposed protocol in terms of network lifetime:
(a) $\alpha = 1$ and (b) $\alpha = 2$.

Overall, Fig. 9 illustrates the performance comparison of the three protocols in terms of network lifetime, for $\alpha = 1$ and $\alpha = 2$, respectively. The figure shows that the proposed MRETDC protocol outperforms both SEP and TSEP with an approximate increase of 280% and 20%, respectively, in terms of network lifetime, thus demonstrating the effectiveness of the proposed protocol. The proposed protocol leverages the heterogeneity in energy level among nodes by assigning the highest energy level to the extreme nodes, resulting in a lower number of dead nodes compared to advanced, intermediate, and normal nodes. As normal nodes tend to deplete their energy at a faster rate, electing advanced and extreme nodes as cluster heads extends the network lifetime. This impact of energy level heterogeneity results in greater network longevity.

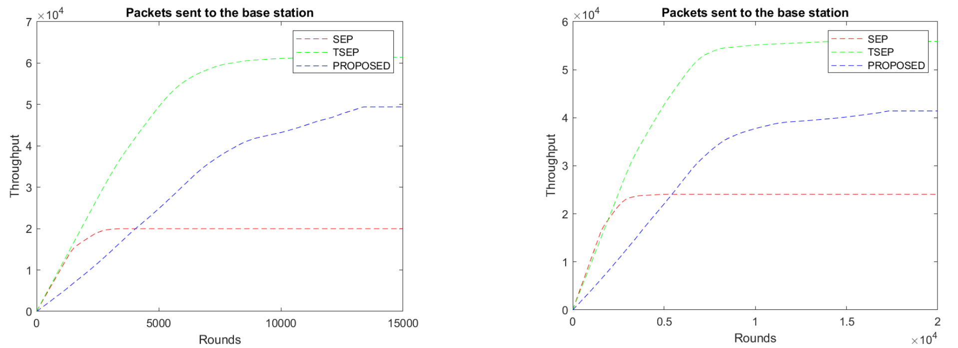
The performance of the proposed protocol is compared with the SEP and TSEP protocols in terms of throughput, as illustrated in Figs. 10 and 11 for $\alpha = 1$ and $\alpha = 2$, respectively. The x-axis represents the number of rounds, while the y-axis denotes the throughput, measured as the number of packets transmitted from cluster heads to the base station per round.

As shown in Fig. 10(a), the throughput of the proposed protocol is 35,006, while that of SEP and TSEP are 14,850 and 46,020, respectively. In Fig. 10(b), the proposed protocol has a throughput of 34,875, while SEP and TSEP have throughputs of 17,744 and 42,290, respectively. In Fig. 11(a), the proposed protocol shows a throughput of 49,421, while SEP and TSEP have throughputs of 19,990 and 61,433, respectively. Finally, in Fig. 11(b), the proposed protocol's throughput is 41,419, whereas SEP and TSEP have throughputs of 24,073 and 55,898, respectively. The results show that the throughput of the proposed protocol is higher than that of SEP, but lower than that of TSEP. This is due to the reactive nature of the proposed protocol, which reduces the number of transmissions.



(a) (b)

Fig. 10. The comparison of SEP, TSEP, and the proposed protocol in terms of number of packets transmitted from cluster heads to base station, for $\alpha = 1$:
(a) $m = 0.2$ and $b = 0.3$ and (b) $m = 0.3$ and $b = 0.3$.



(a) (b)

Fig. 11. The comparison of SEP, TSEP, and the proposed protocol in terms of number of packets transmitted from cluster heads to base station, for $\alpha = 2$:
(a) $m = 0.2$ and $b = 0.3$ and (b) $m = 0.3$ and $b = 0.3$.

Table 2. Summary performance

Protocol			Number of rounds		
			FND	**LND**	**Throughput**
$m = 0.2$	SEP	α = 1	1,141	2,934	14,850
		α = 2	1,269	3,454	19,990
	TSEP	α = 1	2,242	6,401	46,020
		α = 2	2,368	11,554	61,433
	Proposed	α = 1	3,084	10,138	35,006
		α = 2	3,480	13,413	49,421
$m = 0.3$	SEP	α = 1	1,214	3,384	17,744
		α = 2	1,417	5,010	24,073
	TSEP	α = 1	2,523	8,525	42,290
		α = 2	2,711	14,232	55,898
	Proposed	α = 1	3,330	10,604	34,875
		α = 2	3,694	17,299	41,419

Furthermore, the proposed protocol also considers the residual energy of the nodes in probability calculation, which guarantees that the nodes with low energy will have less possibility to become cluster heads in each round. Accordingly, the stability of the network is significantly improved by generating the optimal number of cluster heads in each round. However, aggregation and transmission of the data to the base station are usually done by the cluster heads, therefore the overall throughput is decreased in the proposed MRETDC protocol. On the other hand, SEP and TSEP do not consider the residual energy of the nodes thus, the cluster heads per round are increased which helps to improve the throughput. However, there is a high possibility that the nodes with low energy also become cluster heads and this causes reducing network stability. Based on the discussions and results presented in Figs. 4–11, we have summarized the findings in Table 2, which includes lifetime metrics, such as first node dead (FND) and last node dead (LND), and performance metrics in terms of throughput for different values of α and m. It can be inferred from Table 2 that our proposed protocol outperforms the existing baseline protocols (SEP and TSEP) in terms of both network stability period and network lifetime.

6. Conclusion

In this paper, we proposed the MRETDC protocol, an energy-efficient solution for reactive heterogeneous wireless sensor networks. Energy efficiency and network lifetime are crucial factors in the design of WSNs, and our protocol aims to address these issues by modifying the TSEP algorithm. Our approach considers both the residual energy of the nodes in the cluster heads selection process, as well as the average energy of the network. Additionally, we utilize the four heterogeneities of the nodes. Higher energy nodes have a better chance of becoming cluster heads, resulting in improved performance. Moreover, our protocol benefits from the use of a reactive network that only sends data when it reaches a preferred threshold value. This helps to reduce data transmission and decrease the energy consumption of the nodes in the network. Our performance evaluation of the proposed MRETDC protocol showed that it outperforms the existing baseline protocols, SEP and TSEP. Specifically, our protocol achieved approximately 170% and 30% improvement in stability period compared to SEP and TSEP, respectively. Furthermore, our protocol resulted in a network lifetime improvement of approximately 280% and 20% compared to SEP and TSEP, respectively. These results demonstrate the effectiveness of the proposed protocol, especially for applications such as critical event detection and monitoring. In future work, we aim to incorporate an efficient method for sensor node distribution in WSN to preserve energy consumption and extend the network lifetime with a mobile base station. Our proposed MRETDC protocol can serve as a foundation for such efforts, and we believe that it can make significant contributions to the development of energy-efficient and long-lasting WSNs.

Author’s Contributions

Conceptualization, GW. Investigation and methodology, GW. Project administration, SC. Supervision, SC. Writing of the original draft, GW. Writing of the review and editing, GW, DQT, SC. Software, GW. Validation, GW, DQT, SC. Formal analysis, GW.

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Competing Interests

The authors declare that they have no competing interests.

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