



Uneven Clustering Routing Protocol for Geological Disaster Monitoring Sensor Network

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Abstract. Geological disasters frequently occur in the mountainous area which seriously threaten the safety of railways and human life. Although wireless sensor network (WSN) technology can be used in the geological disaster remote monitoring system by deploying sensor nodes in the mountainous area, the difficulties faced in long-term and large-area monitoring, such as limited battery energy of sensor nodes and high energy consumption of long-distance transmission. In order to prolong the network life and extend monitoring range, this paper takes the distribution and the residual energy of sensor nodes into account to propose an uneven clustering multi-hop routing protocol for geological disaster monitoring sensor network which server can use to realize optimal clustering formation and establish energy efficient routing. In our protocol, particle swarm optimization (PSO) algorithm is used to realize dynamic uneven clustering and minimum spanning tree (MST) algorithm is used to establish energy efficient inter-cluster multi-hop routing that will reduce the energy consumption of long-distance transmission. Compared with the previous routing protocols, the simulation results show the superiority of the proposed protocol in balancing energy consumption of sensor nodes, prolonging network life and long-distance low-power transmission.

Keywords: Wireless sensor network · Uneven clustering · Routing protocol · Multi-hop transmission · Particle swarm optimization · Minimum spanning tree

1 Introduction

The railway network in southwest China is usually located around mountainous areas in which the geological disasters, such as debris flow, landslides and rockfalls [1], often occur due to the complex geological structure and the changeable climate. Therefore, it is necessary to build a long-term monitoring system of mountainous environments to give early warning before geological disasters occur and reduce the losses of life and property.

Although wired monitoring instruments, such as Trip wires [2] and geophones [3], are conventionally used to detect geological disasters, it cannot provide any further information once the wire is broken. Moreover, the limited monitoring regions and the high

cost of these instruments cannot achieve the requirement in practical applications [4]. Recently, WSN technology has been widely used in outdoor large-area environmental monitoring which constitutes spatially dispersed sensor nodes meant to record and monitor various physical and environmental conditions. WSN technology has the capability to capture quickly, process, and transmit of critical high-resolution data for real-time monitoring [5, 6]. However, the large-area and long-term of the geological disaster monitoring in mountainous area and the limited energy of sensor batteries, designing an energy-efficient routing protocol to prolong the network life is a vital issue in WSN.

The clustering scheme has better flexibility and scalability which has been considering to be one of the most effective solutions. A number of the current researches on routing protocols are based on the clustering scheme. In routing protocols LEACH [7] and LEACH-C [8], although random cluster head (CH) selection strategy can balance energy consumption of CH nodes in some case, it may cause the hotspot problem [9, 10], the single-hop transmission scheme, in addition, will consume more energy in long-distance transmission scenarios. Reference [11] takes distance of intra-cluster and residual energy of CH nodes into account and uses PSO algorithm to achieve optimal clustering formation. However, the protocol does not consider the distribution of clusters which may cause imbalance energy consumption of inter-cluster. Reference [12] considers various parameters such as intra-cluster distance, BS distance and residual energy of sensor nodes to select CH nodes. Due to several factors are repeatedly considered both in the CH selection and cluster formation, some cluster member nodes far from CH nodes will die prematurely when the CH node selected by the nodes has more residual energy and is far away from these nodes.

Most of the aforementioned routing protocols only consider the CH nodes selection, they do not well consider the uneven distribution of sensor nodes in mountainous area, which cannot well balance the energy consumption of sensor nodes. Moreover, star topology adopted by previous routing protocols will consume more energy of sensor nodes in large-area monitoring sensor network. In order to balance the energy consumption of sensor nodes and improve existing clustering routing protocol, this paper proposes a PSO-based uneven clustering multi-hop routing protocol (PSO-UCRP), which can be used by server to optimize the network topology, balance the energy consumption of sensor nodes and prolong the network life. The major contributions of this paper can be summarized as follows.

- Aiming at the issues of imbalance energy consumption of WSN in geological disaster monitoring caused by uneven distribution of sensor nodes, we propose uneven clustering algorithm based on PSO, which distribute more CH around BS to form unequal size clusters. To do so can reduce the tasks of CH nodes close to BS, achieve load balancing and prolong the network life.
- Aiming at the issues of high energy consumption of long-distance data transmission, we propose an energy efficient inter-cluster multi-hop routing algorithm based on MST. The algorithm takes communication distance and the residual energy as weight and uses Prim algorithm to establish a minimum spanning tree between BS and CHs as the initial route and optimizes the initial route according to the distribution of sensor nodes. Hence, the transmission energy consumption of CH nodes far away from BS is reduced.

The rest of the paper is organized as follows. Section 2 proposes the network and energy models. The overview of PSO is presented in Sect. 3. The design details of PSO-UCRP protocol are introduced in Sect. 4. Simulation experiment results are shown in Sect. 5. The conclusion is presented in Sect. 6.

2 Network and Energy Models

This paper assumes that there are N sensor nodes randomly deploy in a square area (represented by symbol A) of size $M \times M$ and BS is positioned at the boundary of A to form an initial network system model. The assumptions of the initial network model parameters are as follows.

- All sensor nodes are homogeneous and have the same initial energy. BS have infinite Energy.
- All sensor nodes can be selected as CH node and cluster member.
- Each sensor node has a unique ID and can be aware of its own residual energy and location.
- Each sensor node collects data periodically and can adjust the transmit power according to the distance to the receiver.
- After all the sensor nodes are deployed, they are fixed.

In order to establish the energy consumption model, this paper mainly considers energy consumption of sending data, power amplification and the receiver to run the radio electronics. The model adopts the free space and the multi-path fading channel depending on the distance between transmitter and receiver [13, 14]. The energy consumption (E_T) of transmitting a l -bit packet from the transmitter to its receiver over link of distance d can be calculated by Eq. (1).

$$E_{Tx}(l, d) = \begin{cases} l \times E_{elec} + l \times \varepsilon_{fs} \times d^2, & d < d_0 \\ l \times E_{elec} + l \times \varepsilon_{fs} \times d^2, & d \geq d_0 \end{cases} \quad (1)$$

where E_{elec} is the energy consumed by a sensor node transmit 1-bit data. ε_{fs} and ε_{mp} are two amplifier coefficients of free-space model and multi-path fading model respectively and d_0 is threshold distance which can be calculated by Eq. (2). When $d < d_0$, the energy consumption model adopts the free space model, and the amplifier coefficient is ε_{fs} . When $d \geq d_0$, the energy consumption model adopts the multi-path fading model, and the amplifier coefficient is ε_{mp} .

$$d_0 = \sqrt{\varepsilon_{fs}/\varepsilon_{mp}} \quad (2)$$

3 Overview of PSO Algorithm

Particle Swarm Optimization (PSO) algorithm [15] was proposed by Eberhart et al. in 1995. PSO algorithm is based on the foraging behavior of birds in nature, the algorithm

abstract bird as a particle in search space, and the food is abstracted as solution of the problem, the process of birds searching for food can be expressed as the process of particle search for the optimal solution of the problem [16]. The PSO algorithm flow is described as following steps.

Step1. Assume that there are N_P particles deployed in D dimensional space, each particle P_i ($1 \leq i \leq N_P$) has its position $X_{i,d}$ ($1 \leq d \leq D$) and velocity $V_{i,d}$ ($1 \leq d \leq D$) in the d th dimension of the multidimensional space, and the particle P_i can be represented by Eq. (3).

$$P_i = (X_{i,1}, X_{i,2}, \dots, X_{i,D}) \quad (3)$$

Step2. Set a fitness function and calculate the current fitness of P_i . The fitness function is used to evaluate each particle quality of the solution of the problem. The personal best ($Pbest_i$) is the best position of each P_i . The global best ($Gbest$) is the best position of all particles.

Step3. In order to find the optimal solution of the problem throughout the iteration, each particle P_i follows its own best, i.e., $Pbest_i$ and $Gbest$ to update its own velocity and position. In each iteration, Eq. (4) and (5) are the update formulas for velocity and position of the particle respectively.

$$V_{i,d}(t+1) = w \times V_{i,d}(t) + c_1 \times r_1 \times (Pbest_{i,d} - X_{i,d}(t)) + c_2 \times r_2 \times (Gbest - X_{i,d}(t)) \quad (4)$$

$$X_{i,d}(t+1) = V_{i,d}(t+1) + X_{i,d}(t) \quad (5)$$

where t is current iterations, $1 \leq t \leq T_{max}$, T_{max} is the maximum number of iterations. c_1 and c_2 ($0 \leq c_1, c_2 \leq 2$) are the acceleration coefficients. r_1 and r_2 ($0 \leq r_1, r_2 \leq 2$) are random values between 0 and 1. w is self-adapting weight factor and $w = 0.8$ in this paper.

Step4. Use the new position of the particle P_i to calculate the fitness value and update $Pbest_i$ and $Gbest$ for the minimization problem by Eqs. (6) and (7).

$$Pbest_i = \begin{cases} P_i, & \text{if } (Fitness(P_i) < Fitness(Pbest_i)) \\ Pbest_i, & \text{otherwise} \end{cases} \quad (6)$$

$$Gbest = \begin{cases} P_i, & \text{if } (Fitness(P_i) < Fitness(Gbest)) \\ Gbest, & \text{otherwise} \end{cases} \quad (7)$$

According to Eq. (4–7), each particle P_i updates its own velocity and position by the influences of previous velocity ($V_{i,d}(t)$), previous position ($X_{i,d}(t)$), $Pbest_i$ and $Gbest$. After a number of iterations, all particles move toward to $Gbest$ and find the optimal solution in the searching space.

4 Proposed Algorithm

In order to achieve low energy consumption and long-distance transmission in geological disaster monitoring WSN. The proposed algorithm runs in server, which according to the distribution of sensor nodes in mountainous area and the status of each nodes per round to dynamically form the optimal clusters and establish the energy efficient inter-cluster routing. Figure 1 is the completed workflow of PSO-UCRP.

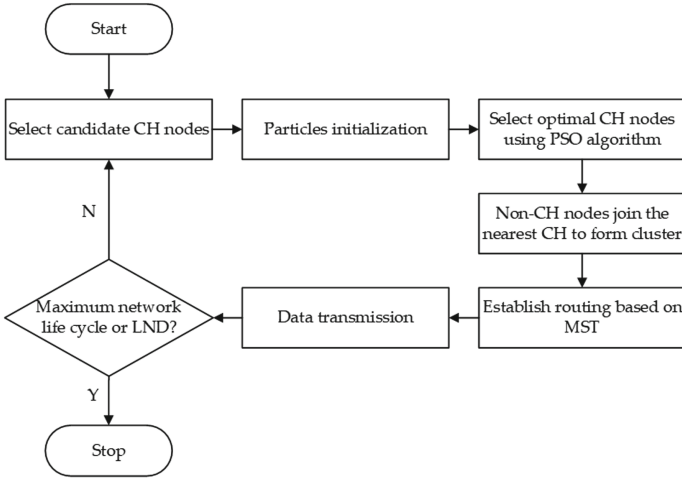


Fig. 1. The workflow of PSO-UCRP

4.1 Particle Representation

In each round of PSO-UCRP, different particles represent different clustering formations, the optimal solution of the particles represents the optimal clustering formation. We select V nodes with higher energy than the average energy of network as the candidate CH nodes at first, then define $K(K < V)$ clusters to the network, thus, there are C_V^K results of clustering in total. According to [8], we have considered only 5% of sensor nodes as CH nodes.

4.2 Initialize Particle Swarm

We randomly select N_p sensor nodes' position as the initial position of particle P_i ($1 \leq i \leq N_p$) in 2-dimensional network area A , thus, each particle $P_i = (X_{i,1}, X_{i,2}) = (x_i, y_i)$ has its own position in A . The distance $d(i, j)$ ($1 \leq j \leq V$) between V candidate CH nodes and particle P_i can be calculated by Eq. (8).

$$d(i, j) = \sqrt{(x_{CHj} - x_i)^2 + (y_{CHj} - y_i)^2} \tag{8}$$

where (x_{CHj}, y_{CHj}) is the position of j th candidate CH node in A .

After generating the particles and calculating the distances between candidate CH nodes and particle P_i , we use the following Algorithm 1 to select K CH nodes in V candidate CH nodes and establish K clusters for each particle.

Algorithm 1. Select CH nodes and form clusters.

Input:

Particle position: $P_i = (x_i, y_i)$ /* $1 \leq i \leq N_p$ */

The position of candidate CH nodes: (x_{CHj}, y_{CHj}) /* $(1 \leq j \leq V)$ */

The number of CH nodes: K

Output:

The nodes' ID for CH nodes: $\{\forall k \in K, \forall i \in N_p | CHID_{P_{i,k}}\}$

Clustering formation: $\{\forall k \in K, \forall i \in N_p | Cluster_{P_{i,k}}\}$

```

1: for  $i = 1$  to  $N_p$  do
2:   for  $j = 1$  to  $V$  do
3:     Calculate  $d(i, j)$  by using Equation (8)
4:   end for
5:   Sort the array  $d(i, j)$  in ascending order and divide them into  $K$  groups equally
6:   for  $k = 1$  to  $K$  do
7:     Randomly select a group member as CH node
8:      $CHID_{P_{i,k}} =$  selected sensor node's ID
9:   end for
10:  Non-CH nodes join the nearest CH to form  $K$  clusters
11: end for

```

4.3 Derivation Fitness Function

Each particle selects K CH nodes by using Algorithm 1, the position and the residual energy of CH nodes can be obtained by CH node's ID, thus, we can use the following fitness function and then use PSO algorithm to achieve the optimal clustering formation.

The fitness function is the bridge between PSO algorithm and optimization problem, different fitness functions can be defined according to the different optimization problems. This paper mainly focuses on the issues of balancing the energy consumption and avoiding the premature death of nodes to define the fitness function. Equation (9) is the fitness function in this paper, it contains four sub-functions.

$$Fitness(P_i) = \alpha_1 \times f_1 + \alpha_2 \times f_2 + \alpha_3 \times f_3 + \alpha_4 \times f_4 \quad (9)$$

where $\alpha_1, \alpha_2, \alpha_3$ and α_4 ($\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 1$) are the weight factors of sub-function respectively. f_1 is defined by CH nodes residual energy. f_2 and f_3 are defined by the distribution of clusters. f_4 is defined by the intra-cluster distance.

4.3.1 Fitness Sub-function of Energy

Due to CH nodes undertake more tasks than non-CH nodes, such as data sending and receiving, routing and forwarding, the energy consumption of them is larger than that of the cluster member nodes in the cluster. In other words, the more the residual energy of CH nodes, the more reliable routing transmission of data in the network can be achieved.

The CH node's ID, obtained by Algorithm 1, can help us to calculate the proportion of CH nodes' energy in network energy to make sure that CH nodes have enough residual

energy without dying soon. Equation (10) is sub-function of energy.

$$f_1(P_i) = \frac{\sum_{j=1}^{N_{alive}} E(n_j)/N_{alive}}{\sum_{k=1}^K E(CH_{P_i,k})/K} \quad (10)$$

where N_{alive} is the number of alive sensor nodes. $E(n_j)$ is the energy of the j th sensor node. $E(CH_{P_i,k})$ is the energy of CH node k which is selected by particle P_i . K is the number of the clusters.

f_1 denotes the ratio of the average energy of the whole network to the average energy of CH nodes, the smaller the f_1 is, the more the residual energy of CH nodes.

4.3.2 Fitness Sub-functions of Distribution of Clusters

The distribution of clusters directly affects CH nodes life, two factors determine the distribution of clusters: the distance between CH nodes and BS and the inter-cluster distance. In order to reduce the energy consumption of forwarding tasks of CH nodes which are close to BS, more CH nodes should be distributed around BS. Moreover, the longer the inter-cluster distance, the more transmission energy the CH nodes consume. Thus, two sub-functions of distribution of clusters are proposed as following Eq. (11) and (12).

$$f_2(P_i) = \frac{\sum_{i=1}^K d(BS, CH_{P_i,k})/K}{d(BS, NC)} \quad (11)$$

where $d(BS, CH_{P_i,k})$ is the distance between BS and k th CH node of particle P_i . $d(BS, NC)$ is the distance between BS and network area center.

Sub-function f_2 denotes the ratio of the average distance between CH nodes and BS to the distance between BS and network area center. The smaller the f_2 is, the more the CH nodes around the BS.

$$f_3(P_i) = \max\{\forall k \in K | \text{Overlap}(\text{Cluster}_{P_i,k})\} \quad (12)$$

where $\text{Overlap}(\text{Cluster}_{P_i,k})$ is the overlapping ratio of cluster k , and according to the following Fig. 2, we can calculate the overlapping rate of cluster by Eq. (13).

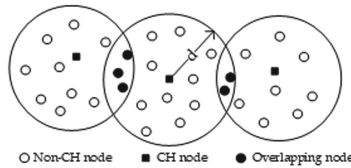


Fig. 2. The overlapping ratio of cluster

In Fig. 2, d is the average distance between cluster member nodes and CH node.

$$\text{Overlap}(\text{Cluster}_{P_i,k}) = \left(\sum_{j=1}^{C_{overlap}} \frac{N_{overlap,C_j}}{N_{intra,C_j}} \right) / C_{overlap} \quad (13)$$

where $C_{overlap}$ is the number of overlapping clusters. $N_{overlap,C_j}$ and N_{intra,C_j} are the number of overlapping nodes and the number of sensor nodes in cluster j respectively.

Sub-function f_3 denotes the maximum overlapping ratio of clusters of particle P_i , a smaller value of f_3 means more reasonable inter-cluster distance which can prevent the imbalance energy consumption of CH nodes caused by too dense or too sparse distribution.

4.3.3 Fitness Sub-function of Intra-cluster Distance

The intra-cluster distance determines the energy consumption of cluster member nodes. The CH nodes should be distributed as closely as possible to the center of the cluster to balance the transmission energy consumption of cluster members. The sub-function of intra-cluster distance in is shown as Eq. (14).

$$f_4(P_i) = \max \left\{ \forall k \in K \left| \frac{\sum_{j=1}^{N_{intra,C_k}} d(CH_{P_i,k}, n_j)}{N_{intra,C_k} - 1} \right| \right\} / d_0 \quad (14)$$

where $d(CH_{P_i,k}, n_j)$ is the distance between cluster member j and CH node. N_{intra,C_k} is the number of sensor nodes in cluster k .

f_4 denotes the maximum average distance of intra-cluster, a smaller value of f_4 means CH nodes are distributed closely at the center of clusters.

4.4 Optimal Clustering Formation

The optimal clustering formation process based on PSO algorithm is as follows.

Algorithm 2. Optimal Clustering formation based on PSO.**Input:**Set of sensor nodes: $\mathbf{S} = \{s_1, s_2, \dots, s_N\}$ The number of particles: N_p The number of CH nodes: K Maximum iterations of PSO: T_{max} **Output:**The nodes' ID for optimal CH nodes: $\{\forall k \in K | CHID_k\}$ Optimal clustering formation: $\{\forall k \in K | Cluster_k\}$

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1: Select  $V$  sensor nodes with higher energy than the average energy of network as
   candidate CH nodes
2: for  $i = 1$  to  $N_p$  do
3:    $P_i = (x_i, y_i)$  /*  $(x_i, y_i)$  is the position of sensor node */
4:   Get  $CHID_{P_i,k}$  using Algorithm 1 and establish  $K$  clusters
5:   Calculate  $Fitness(P_i)$  /* Using Equation (9) */
6:    $Pbest_i = P_i$ 
7:   if  $Fitness(P_i) < Fitness(Gbest)$  then
8:      $Gbest = P_i$ 
9:      $\{\forall k \in K | CHID_k\} = \{\forall k \in K, \forall i \in N_p | CHID_{P_i,k}\}$ 
10:  end if
11: end for
12: for  $t = 1$  to  $T_{max}$  do
13:   for  $i = 1$  to  $N_p$  do
14:    Update velocity and position of particle  $P_i$  using Equation (4) and (5)
15:    if  $Fitness(P_i) < Fitness(Pbest_i)$  then
16:       $Pbest_i = P_i$ 
17:      if  $Fitness(P_i) < Fitness(Gbest)$  then
18:         $Gbest = P_i$ 
19:         $\{\forall k \in K | CHID_k\} = \{\forall k \in K, \forall i \in N_p | CHID_{P_i,k}\}$ 
20:      end if
21:    end if
22:  end for
23: end for
24: Form  $K$  optimal clusters according to  $CHID_k$ 

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4.5 Establish Inter-cluster Routing

After determining the position of CH nodes, the distribution of clusters is also determined, it is necessary to establish an energy-efficiency routing in network before transmit data to BS. This paper takes transmission distance and the residual energy of CH nodes as edge weight then uses Prim algorithm to create a minimum spanning tree (MST) as inter-cluster routing. The following steps are the establishment of routing.

Step1. Add CH nodes and BS as vertexes to set $V = \{BS, CH_1, CH_2, \dots, CH_K\}$.

Step2. Calculate weight of edges by following Eq. (15).

$$Weight_{i,j} = \frac{d_{vertex(i,j)}/d_0}{E_i + E_j} (1 \leq i \leq K+1) \quad (15)$$

where $d_{vertex(i,j)}$ is the distance between vertex i to vertex j , $d_{vertex(i,j)}$ divided by d_0 is normalized to adjust its value in the range $[0, 1]$. E_i and E_j are the residual energy of CH_i and CH_j respectively.

Step3. Add vertex BS as root to set U ($U = \{BS\}$).

Step4. In set $V - U$, select the vertex with minimum weight to the vertexes in set U and add it to set U .

Step5. Repeat Step4 until $V = U$.

Step6. If the distances between CH node and BS are less than d_0 , so these CHs transmit data to BS directly. If the distances from cluster member nodes to CH node are less than that distance to BS, so these cluster member nodes transmit data to BS directly.

Figure 3 is the result of optimal clustering formation and eventual routing in simulation environment with 200 sensor nodes deployed in $200\text{ m} \times 200\text{ m}$ network area. It can be seen that CH nodes are distributed around BS as close as possible and are not distributed too dense or too sparse and the transmission distances between clusters are as short as possible. The residual energy of the sending nodes and receiving nodes is considered in routing establishment process to make sure the CH nodes to have enough energy to forward packets. Hence, the consumption of energy in data transmission is significantly reduced and balanced.

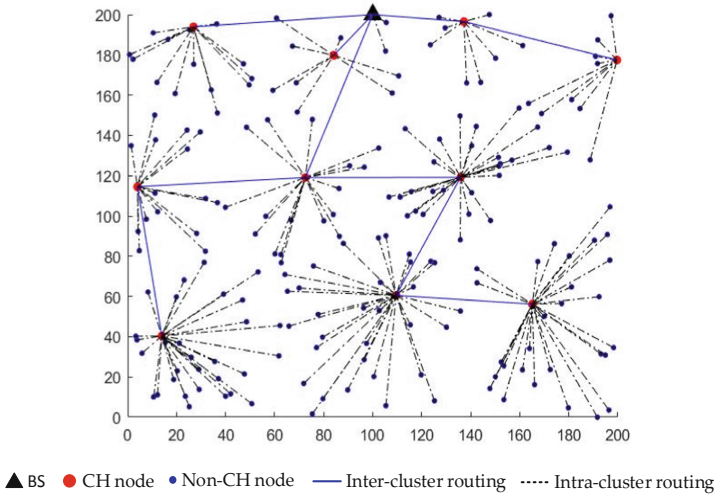


Fig. 3. Clustering and routing diagram in simulation environment

5 Simulation Experiments and Results

To evaluate the performance of PSO-UCRP, MATLAB is used to perform simulations. All comparison protocols adopt the following simulation principles.

- The operation of protocol is broken up into rounds.
- In each round, non-CH nodes send a packet to their own CH, then CH aggregates the received packets and sends it to the next hop.

- In each round, we recorded and compared the number of packets received by BS, the number of alive nodes and the residual energy of network. Moreover, the round in which the first dead node occurs, the round in which half of nodes die and the round in which 80% nodes die are also recorded and compared.
- The sensor nodes consume energy in transmitting packets and only the sensor nodes with enough energy can send packets successfully. The adopted network and energy models show in Sect. 2.

Table 1. Simulation parameters.

Parameter	Value
Area of network	$A = M \times M (M = 200 \text{ m}, 400 \text{ m})$
Base station position	$(M/2, M)$
Number of sensor nodes	$n = 100, 200$
Initial energy of sensor nodes	$E_0 = 0.5 \text{ J}$
Energy consumption on circuit	$E_{elec} = 50 \text{ nJ/bit}$
Free-Space amplifier coefficient	$\varepsilon_{fs} = 10 \text{ pJ/bit/m}^2$
Multi-path fading amplifier coefficient	$\varepsilon_{mp} = 0.0013 \text{ pJ/bit/m}^4$
Packet size	$l = 4000 \text{ bit}$
Maximum life cycle of network	$r = 2500 \text{ rounds}$
The acceleration coefficients	$c_1 = c_2 = 2$
The weight factors of fitness function	$\alpha_1 = 0.3, \alpha_2 = 0.2, \alpha_3 = 0.3, \alpha_4 = 0.2$

The simulation parameters of network are shown in Table 1.

The simulation experiments were carried out on LEACH-C, HEED, PSO-C, PSO-ECHS and PSO-UCRP in the corresponding network circumstances. The proposed algorithm is to balance the energy consumption of network by clustering. Therefore, this paper mainly compares the classical and PSO-based clustering routing protocols.

Table 2 shows 100 sensor nodes' death states of the protocols in $200 \text{ m} \times 200 \text{ m}$ network area.

where FND denotes the round in which the first node dead occurs. HND denotes the rounds in which half of nodes die. LND denotes the round in which 80% nodes die.

Table 2 indicates that the PSO-UCRP protocol has better performance in balance energy consumption of sensor nodes and in prolong network life than the other four

Table 2. The death states of sensor nodes.

Death state	LEACH-C	HEED	PSO-C	PSO-ECHS	PSO-UCRP
FND	326	92	623	787	945
HND	1007	1453	1102	1374	1751
LND	1371	1640	1826	1512	1901

protocols under the same network conditions. Compared with LEACH-C, HEED, PSO-C and PSO-ECHS, the number of running rounds of PSO-UCRP is increased by 38.6%, 15.9%, 4.1% and 25.7% respectively.

Table 3 shows the average (AVE) and standard deviation (STD) of residual energy of nodes in the 500th round in the 200 m × 200 m network area with 100 sensor nodes.

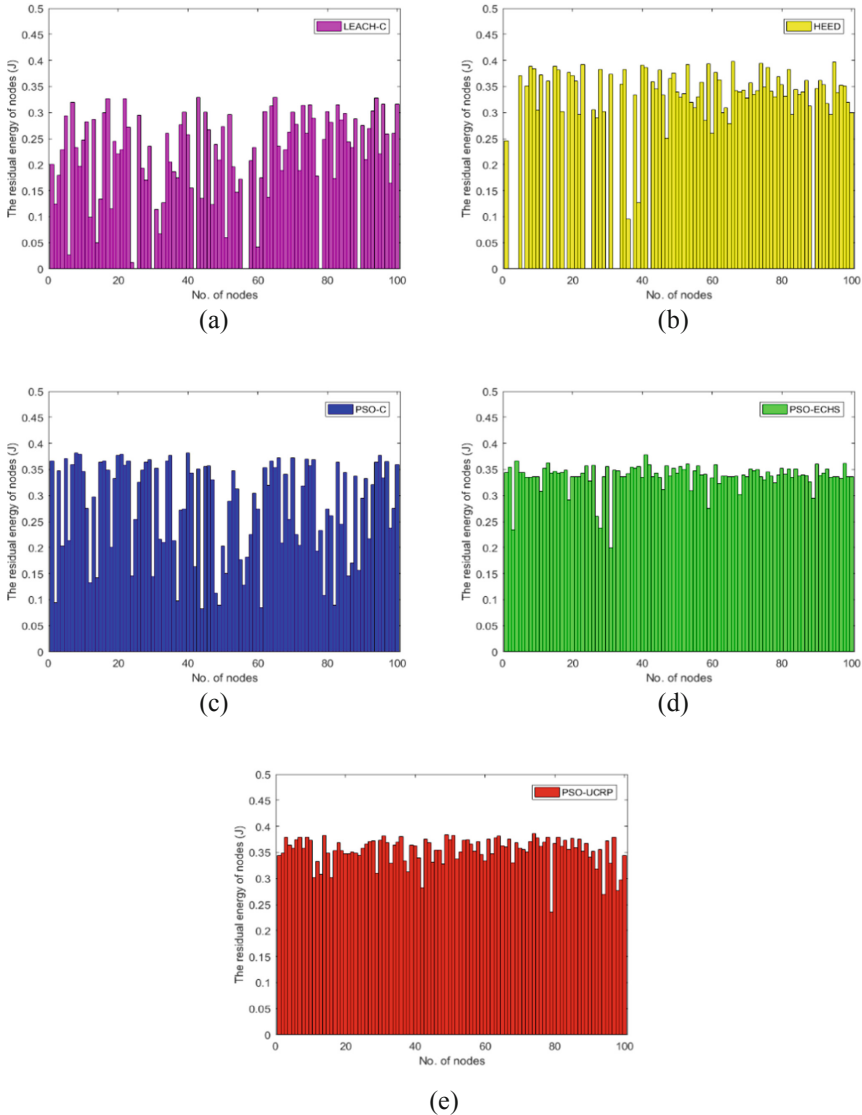


Fig. 4. Residual energy of nodes under different protocols in the 500th round: (a) LEACH-C; (b) HEED; (c) PSO-C; (d) PSO-ECHS; (e) PSO-UCRP

Table 3. Average and standard deviation of residual energy of nodes in 500th round.

	LEACH-C	HEED	PSO-C	PSO-ECHS	PSO-UCRP
AVE	0.2253	0.2874	0.2775	0.3361	0.3517
STD	0.1052	0.1231	0.0926	0.0266	0.0263

(a)–(e) in Fig. 4 are the residual energy of 100 sensor nodes in the 500th round in $200\text{ m} \times 200\text{ m}$ network area under the protocols of LEACH-C, HEED, PSO-C, PSO-ECHS and PSO-UCRP respectively.

As we can see in (a)–(e) in Fig. 4, in the 500th round in same network circumstances, more residual energy of nodes in PSO-UCRP than the other four protocols, and PSO-UCRP has the smallest standard deviation of residual energy in Table 3 which turns out that the energy consumption of nodes in the protocol is more balance than the other four protocols.

Figure 5 shows the number of alive sensor nodes in each round in $200\text{ m} \times 200\text{ m}$ network area.

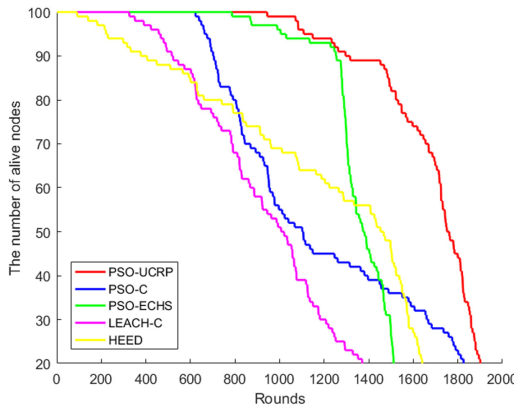


Fig. 5. The number of alive nodes under different protocols (100 sensor nodes)

It can be seen that the number of alive sensor nodes of PSO-UCRP begins to decrease later than the other four protocols and the round when the first node’s death occurs is significantly delayed. Figure 6 shows how the energy consumption of the five routing protocols in each round varies in $200\text{ m} \times 200\text{ m}$ network area.

The energy of network in PSO-UCRP is decreased slower than the other four protocols, which means that the protocol can significantly balance the energy consumption of sensor nodes.

Figure 7 indicates the data throughputs of network under different protocols in $200\text{ m} \times 200\text{ m}$ net. And it can be seen that, although several protocols prolong the network life, the packets received by BS in PSO-UCRP protocol is the highest of the five compared protocols. In other words, the protocol can collect more data in each round.

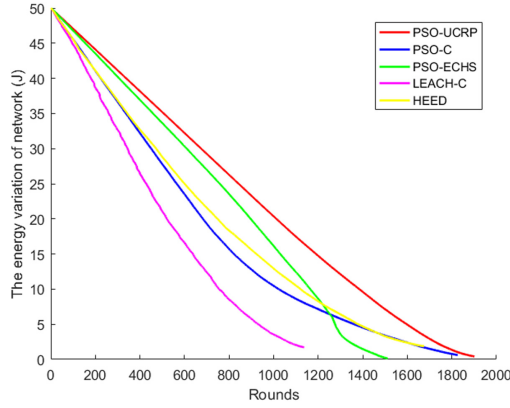


Fig. 6. Energy consumption of network under different protocols (100 sensor nodes)

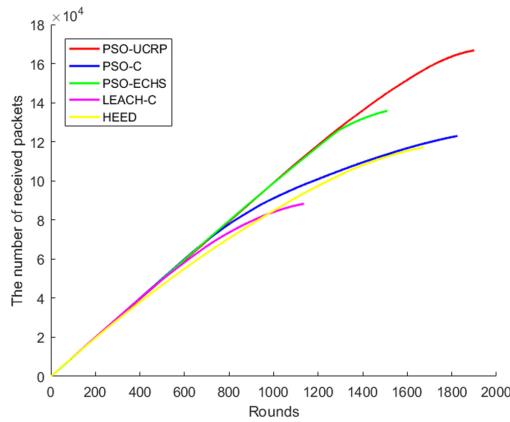


Fig. 7. The number of packets received by BS under different protocols (100 sensor nodes)

We also compared the scalability of the network nodes number and network areas of the five protocols, the LNDs of LEACH-C, HEED, PSO-C, PSO-ECHS and PSO-UCRP were tested in the 200 m × 200 m and 400 m × 400 m network areas with different number of sensor nodes, respectively. Table 4 shows the LNDs of the five protocol in 400 m × 400 m network area with different number of sensor nodes. Table 5 shows the LNDs of the five protocol in 200 m × 200 m network area with different number of sensor nodes.

Table 4 and 5 show that in the network area with different number of nodes, the LNDs of the PSO-UCRP occurred later than the other four protocols. The results show that due to the balanced energy consumption of network, PSO-UCRP protocol has better scalability for network area with different number of sensor nodes and different sizes.

The experiment results show that, although several protocols prolong the network life, the packets received by BS in PSO-UCRP protocol is the highest one, which means the energy consumption of sensor nodes in our protocol are more balanced and have enough energy to transmit packets.

Table 4. LND of different protocols in the 400 m × 400 m network area

Number of nodes	100	200
LEACH-C	547	693
HEED	661	900
PSO-C	733	1130
PSO-ECHS	735	1021
PSO-UCRP	848	1144

Table 5. LND of different protocols in 200 m × 200 m network area

Number of nodes	100	200
LEACH-C	1371	1755
HEED	1640	1770
PSO-C	1826	2019
PSO-ECHS	1512	1803
PSO-UCRP	1901	2152

6 Conclusions

Considering the large-area of monitoring in the mountainous area, the uneven distribution of sensor nodes and the battery energy are limited. This paper proposes an uneven clustering multi-hop routing protocol for geological disaster monitoring sensor network to balance the energy consumption of sensor nodes. Simulation experiments showed that compared with LEACH-C, HEED, PSO-C and PSO-ECHS, PSO-UCRP significantly delays the time of first dead node occurs, prolongs the network life and improves the success rate of packets received by BS. In other words, PSO-UCRP can achieve long-term and large-area requirements of geological disaster monitoring in the mountainous area and can be adopted by other outdoor wireless monitoring systems.

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References

1. Kotta, H.Z., Rantelobo, K., Tena, S., Klau, G.: Wireless sensor network for landslide monitoring in nusa tenggara timur. *TELKOMNIKA (Telecommun. Comput. Electron. Control)* **9**(1), 9–18 (2011)
2. Huang, Y.M., Chen, W.C., Fang, Y.M., Lee, B.J., Chou, T.Y., Yin, H.Y.: Debris flow monitoring - a case study of Shenmu area in Taiwan. *Disaster Adv.* **6**(11), 1–9 (2013)

3. Hsiao, T., Lee, B., Chou, T., Lien, H., Chang, H.L.: Debris flow monitoring system and observed event in Taiwan: a case study at Aiyuzi river. *Wuhan Univ. J. Nat. Sci.* **12**, 610–618 (2007). <https://doi.org/10.1007/s11859-006-0298-4>
4. Lee, H., Ke, K., Fang, Y., Lee, B., Chan, T.: Open-source wireless sensor system for long-term monitoring of slope movement. *IEEE Trans. Instrum. Meas.* **66**(4), 767–776 (2017)
5. Behera, T.M., Mohapatra, S.K., Samal, U.C., Khan, M.S., Daneshmand, M., Gandomi, A.H.: I-SEP: an improved routing protocol for heterogeneous WSN for IoT-based environmental monitoring. *IEEE Internet Things J.* **7**(1), 710–717 (2020)
6. Ramesh, M.V.: Design, development, and deployment of a wireless sensor network for detection of landslides. *Ad Hoc Netw.* **13**(Part A), 2–18 (2014)
7. Heinzelman, W.R., Chandrakasan, A., Balakrishnan, H.: Energy-efficient communication protocol for wireless microsensor networks. In: *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences*, Maui, HI, USA, vol. 2 (2000). 10 pp.
8. Heinzelman, W.B., Chandrakasan, A.P., Balakrishnan, H.: An application-specific protocol architecture for wireless microsensor networks. *IEEE Trans. Wireless Commun.* **1**(4), 660–670 (2002)
9. Jannu, S., Jana, P.K.: A grid based clustering and routing algorithm for solving hot spot problem in wireless sensor networks. *Wireless Netw.* **22**(6), 1901–1916 (2015). <https://doi.org/10.1007/s11276-015-1077-y>
10. Singh, S.K., Kumar, P., Singh, J.P.: An energy efficient protocol to mitigate hot spot problem using unequal clustering in WSN. *Wireless Pers. Commun.* **101**(2), 799–827 (2018). <https://doi.org/10.1007/s11277-018-5716-3>
11. Latiff, N.M.A., Tsimenidis, C.C., Sharif, B.S.: Energy-aware clustering for wireless sensor networks using particle swarm optimization. In: *2007 IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications*, Athens, pp. 1–5 (2007)
12. Rao, P.C.S., Jana, P.K., Banka, H.: A particle swarm optimization based energy efficient cluster head selection algorithm for wireless sensor networks. *Wireless Netw.* **23**(7), 2005–2020 (2016). <https://doi.org/10.1007/s11276-016-1270-7>
13. Shen, J., Wang, A., Wang, C., Hung, P.C.K., Lai, C.: An efficient centroid-based routing protocol for energy management in WSN-assisted IoT. *IEEE Access* **5**, 18469–18479 (2017)
14. Hamida, E.B., Chelius, G.: A line-based data dissemination protocol for wireless sensor networks with mobile sink. In: *2008 IEEE International Conference on Communications*, Beijing, pp. 2201–2205 (2008)
15. Eberhart, R., Kennedy, J.: A new optimizer using particle swarm theory. In: *MHS 1995, Proceedings of the Sixth International Symposium on Micro Machine and Human Science*, Nagoya, Japan, pp. 39–43 (1995)
16. Liang, Y., Yu, H.: PSO-based energy efficient gathering in sensor networks. In: Jia, X., Wu, J., He, Y. (eds.) *MSN 2005*. LNCS, vol. 3794, pp. 362–369. Springer, Heidelberg (2005). https://doi.org/10.1007/11599463_36