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Clustering Hierarchy Protocol in Wireless Sensor Networks Using an Improved PSO Algorithm

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ABSTRACT Maximizing network lifetime is a major objective for designing and deploying a wireless sensor network. Clustering sensor nodes is an effective topology control approach helping achieve this goal. In this paper, we present a new method to prolong the network lifetime based on the improved particle swarm optimization algorithm, which is an optimization method designed to select target nodes. The protocol takes into account both energy efficiency and transmission distance, and relay nodes are used to alleviate the excessive power consumption of the cluster heads. The proposed protocol results in better distributed sensors and a well-balanced clustering system enhancing the network's lifetime. We compare the proposed protocol with comparative protocols by varying a number of parameters, e.g., the number of nodes, the network area size, and the position of the base station. Simulation results show that the proposed protocol performs well against other comparative protocols in various scenarios.

INDEX TERMS WSN, clustering, energy efficiency, network lifetime, PSO.

I. INTRODUCTION

A wireless sensor network (WSN) is a self-organized wireless network system consisting of a number of sensors, which gather information from their surrounding environments and transmit it to a data sink or a base station (BS) [1]. In WSN applications, the main objective is to monitor and collect sensor data and then transmit the data to the BS. Sensors in different regions of the field can collaborate in data collection, and provide more accurate reports about their local regions. Most deployed WSNs measure physical phenomena like temperature, pressure, humidity, or location of objects [2], to improve the fidelity of reported measurements, and data aggregation reduces the communications overhead in the network, leading to significant energy savings [3], [4]. The characteristics of low-cost, low-power, and multifunctional sensors have rendered WSNs very attractive [5]. Nowadays, with the development of cloud technology [6], WSNs have been rapidly deployed many practical applications, including home security, battle-field surveillance, monitoring movement of wild animals in the forest, healthcare applications [7], etc. Recently, extensive research efforts have been dedicated to explore new roles for WSNs in remote and inaccessible environments [8].

In a sensor network, each node is both a sensor and a router, and its computing capability, storage capacity and communications ability are limited [9]–[11]. Moreover, in many WSN applications, sensor nodes are deployed in harsh environments, which makes the replacement of failed nodes either difficult or expensive. Thus, in many scenarios, a wireless node must operate without battery replacement for an extended period of time [12]. Consequently, energy efficiency is the most critical issue when designing a network routing protocol with the objective of prolonging the network lifetime[5], [13], [14].

Energy consumption can be efficiently managed through adjusting the network topology and regulating the nodes' transmission power levels in the routing protocol [15], [16]. The clustering technique is useful in reducing power usage in routing protocols [17]. In a clustering architecture, sensor nodes are organized into clusters, where the sensor nodes with lower energy can be used to perform sensing tasks, and send the sensed data to their cluster head at a short distance [18]–[21]. A node in a cluster can be chosen as the cluster head (CH) to eliminate correlated data from the members of the cluster, with the objective of reducing the amount of the aggregated data transmitted to the BS [22], [23].

The clustering approach is able to increase network longevity and to improve energy efficiency by minimizing overall energy consumption and balancing energy consumption among the nodes during the network lifetime [24], [25]. Moreover, it is capable of alleviating channel contention and packet collisions, resulting in better network throughput under high load [26], [27].

This paper focuses on energy efficiency routing protocols for WSNs with the aim of prolong network longevity. To contextualize our research, we first discuss a few key related protocols in Section I-A, and then outline our contributions in Section I-B.

A. RELATED WORK

Under the constrains of limited energy, bandwidth and computation capabilities, many routing protocols are designed to improve network efficiency. The LEACH protocol [28] is one of the most well-known WSN clustering protocols, which selects a CH based on a predetermined probability of rotating the CH role among the sensor nodes so as to avoid fast depletion of the CH's energy. However, the selection of CHs is random. As a result, a node with low energy may be chosen as the CH, and the CHs may not evenly distributed. Furthermore, the LEACH protocol requires that the transmission between the CHs and the BS be completed via a single hop, which consumes a large amount of energy and destroy the energy balance of nodes if the CHs are located far away the BS. The LEACH-centralized (LEACH-C) protocol is proposed as an improvement over LEACH, which uses a centralized clustering algorithm to form the clusters. LEACH-C enhances network performance through creating better clusters by dispersing the CHs throughout the network. The information on the residual energy of the nodes is taken into account in the probability formula, so the nodes with higher energy are more likely to be selected as the CHs. However, LEACH and LEACH-C are unable to use intelligent the CH selection methods, and the distribution of CHs is random, resulting in overload energy consumption. As a result, BCDCP [21] is proposed to form more balanced clusters. In BCDCP, each cluster head servers an approximately equal number of member nodes so as to avoid cluster head overload, and the CHs utilize CH-to-CH routing to transfer data to the BS.

The above protocols focus only on uniform energy consumption of the nodes. To further prolong network lifetime, some location-aware protocols are proposed to reduce the transmission costs among the nodes. In the HEED protocol [17], cluster heads are selected based on the nodes' residual energy plus a secondary parameter, such as the nodes' proximity to its neighbors or node degree. The cluster heads send data to the BS via multi-hop communications. HEED ensures that only one CH within a certain range achieves the uniform CH distribution across the network. Therefore, the head nodes consume a great deal of power in the HEED protocol, resulting in their quick depletion of energy. The EECS protocol [29] leads to a fair distribution for cluster heads, in which cluster heads are selected based on the residual energy and location of nodes. In EECS, a competitive algorithm is suggested for the CH selection phase, and a fixed competition range is specified for each volunteer node. Any node that finds itself more powerful than the others in its competition radius will introduce itself as a CH and broadcasts to all the other nodes. However, this algorithm causes a potential problem in dense networks for having too many nodes competing for being a CH. The TCAC protocol [30] improves the performance of the EECS protocol, which dynamically controls the nodes' transmission power levels to minimize network energy consumption while ensuring inter-cluster connectivity. The selected CHs send the data to the BS directly. The Hausdorff clustering method [31] introduces a greedy algorithm to select cluster heads based on the location, communication efficiency and network connectivity, while the clusters are formed only once. Therefore residual energy of the nodes consume quickly when the clusters are organized inefficiently at the first time. In [32], a LECP-CP protocol is proposed, and the core of which includes a novel cluster head election algorithm and an inter-cluster communication routing tree construction algorithm, both based on the predicted local energy consumption ratio of nodes. What's more, the protocol also provide a more accurate and realistic cluster radius to minimize the energy consumption of the entire network.

In most applications, the BS is far from the sensor network, and thus the cluster heads have to consume much more energy than the other nodes. Thus, task allocation can be done in such a way that the sensor nodes paly a significant role in improving energy efficiency. For example, relay nodes can be used to balance the heavy consumption of the cluster heads. In SEECH [33], some nodes with higher residual energy are selected as the relay nodes, and the CH chooses the closest relay node as its next hop. Thus, the CH collect and aggregates data from all the cluster members, and then transfers the data to the relay node, which relays the data to the BS. In this way, the relay node can share the CH's data transmission, and thus helps offload the CH's energy consumption. However, two or more CHs may choose the same relay nodes, which will expedite the energy depletion of the selected relay nodes. In addition, extra energy consumption is required when a CH chooses its relay node. Moreover, the location of nodes is not taken into consideration in the selection of relay nodes.

B. CONTRIBUTIONS

Although the aforementioned protocols are able to prolong network lifetime to some extent, there is no guarantee that the selected node is best fit as a cluster head. There are two main reasons. Firstly, some nodes with lower energy are probabilistically determined as the cluster heads, which will exacerbate the energy consumption of these nodes. Secondly, some nodes are not suitable to be at the center of a cluster because of their location. If a node near the boundary of the network is selected as a cluster head, energy consumption will increase because the cluster head is far from the BS.

In our previous work, we have used a non-linear optimization method in the algorithm to select cluster heads [34]. In this paper, we propose a new clustering protocol using an improved particle swarm optimization (PSO) algorithm. Firstly, we use relay nodes to offload the energy consumption of the CHs. Different from these protocols, in our paper, every cluster head has a corresponding relay node in our protocol, which has two benefits: 1) the cluster heads do not need to consume additional energy to choose their next-hop node; 2) channel contention which arises when choosing relay nodes by the cluster heads can be avoided. In addition, the selection of the relay nodes is based on not only the residual energy, but also the distance to the corresponding cluster head and the BS. Then, two fitness functions are generated which determine whether a node is selected as a cluster head or a relay node, in consideration of both their location and residual energy. The selection of the cluster heads and relay nodes as is formulated an NP-hard problem. And an improved PSO algorithm is proposed to achieve the optimum solution.

The remainder of this paper is organized as follows. In Section II, we describe the model used in this work. The proposed clustering protocol is described and formulated as an optimization problem in Section III. Section IV proposes a node-updating algorithm based on PSO. Section V analyzes several properties of our algorithms. Experimental results and discussions are provided in Section VI. Finally, concluding remarks are drawn in Section VII.

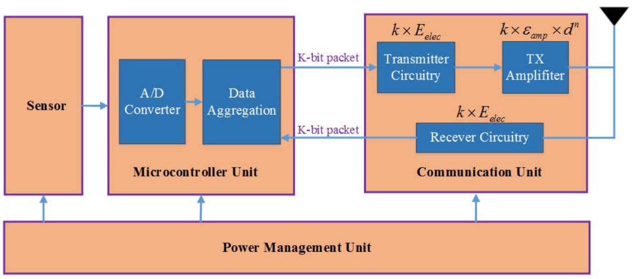

FIGURE 1. Sensor node components and radio energy model.

II. SYSTEM MODEL

A. NETWORK MODEL

A wireless sensor network consisting of N sensor nodes is considered, which is deployed in a field to monitor the environment continuously. Fig. 1 illustrates the components of a sensor node, including the microcontroller unit, communication unit and power management unit. The following assumptions about the sensor network and sensor nodes are made:

1) Each sensor node has the same ability to operate either in the sensing mode to perceive environmental parameters, or in the communication mode to send data among one another or directly to the BS, and each node can gather data packets from the cluster members when acting as the CH;
2) Each node has a data link capable of handling all data traffic;
3) Each node is assigned an index according to its location;
4) The sensor nodes and the BS are stationary after deployment, which is typical for sensor network applications;
5) Initial energy is fair for each sensor node, and the network is considered homogeneous;
6) All the nodes are left unattended after deployment. That is, it is impossible to recharge battery;
7) All the nodes measure the environmental parameters at a fixed rate and send data periodically to the target nodes;
8) Each node has a fixed number of transmission power levels. The nodes are capable of adjusting their transmission power in accordance with the distance to the desired recipient;
9) The links between nodes are symmetric. A node can estimate the distance to another node only based on the received signal power;
10) The sensed information is highly correlated, so the cluster head aggregate the data gathered from its cluster into a fixed-length packet; and
11) The BS is externally powered.

B. ENERGY CONSUMPTION MODEL FOR WSN NODES

A simplified model shown in Fig. 1 is considered in this paper for communication energy consumption in consideration of path losses [5], [28]. Either the free space (d^2 power loss) or the multipath fading (d^4 power loss) channel model is employed, according to the distance between the transmitter and receiver. Power control can be used to compensate for this loss. If the distance is less than a threshold d_0, the free space model is used; otherwise, the multipath model is adopted. The required energy for transmitting a k-bit packet over distance d is

$$E_{TX}(k,d) = \begin{cases} k \times E_{elec} + k \times E_{fs} \times d^2, & \text{if } d \le d_0 \\ k \times E_{elec} + k \times E_{mp} \times d^4, & \text{if } d > d_0 \end{cases} \tag{1}$$

where E_{TX} is the transmission energy, E_{fs} is the energy used for reception, d is the distance between two nodes or between a node and the sink, E_{elec} is the energy dissipated per bit to the transmitter or receiver circuit, which depends on factors such as channel coding, modulation, filtering, and spreading of the signal. E_{fs} and E_{mp} depend on the transmitter amplifier model, k is the length of the data transmitted, and d_0 is the transmission distance threshold given by

$$d_0 = \sqrt{\frac{E_{fs}}{E_{mp}}}. \tag{2}$$

To receive a k-bit message, the radio consumes the following energy

$$E_{RX}(k) = k \times E_{elec}. \tag{3}$$

C. NETWORK LIFETIME MODEL

In most applications, a network would still function effectively when some nodes fail. Especially when a large number of sensor nodes are deployed in an area, a node has several adjacent neighbors equipped with the same sensing equipment, so that the network will be able to cope with the failure of some nodes. Thus, the time until the first node died (FND) is not the only metric to evaluate the network lifetime [1], [2]. As a result, the lifetime that a part of nodes die (PND) is a more effective metric when evaluating the performance in scenarios of high node density [3], [4]. We describe the lifetime of the network as follows:

$$T_N^k = T[\xi = \frac{k}{N}]. \tag{4}$$

where N is the number of sensors in the network. k is the number of alive nodes. The equation shows that the definition of PND lifetime is time until the fraction of alive nodes falls below a predefined threshold ξ.

III. CLUSTERING PROTOCOL

In our protocol, nodes are classified into the CHs, relay nodes (RNs) and common nodes (CNs). The operation of the protocol includes two phases, i.e., the clustering setup phase and data transmission phase. The two phases are performed in each round of the network operation and repeated periodically. In the clustering setup phase, the clusters, CHs and RNs as well as the path between each cluster and the sink (or the BS) are determined, and then the network is organized. In the data transmission phase, the CHs collect data from all the cluster members and transfer to the relay nodes which then relay the data to the BS according to the topology determined in the previous phase. Fig. 2 depicts the general topology of the protocol. The selection of the CHs and RNs is described in detail in Sections A and B.

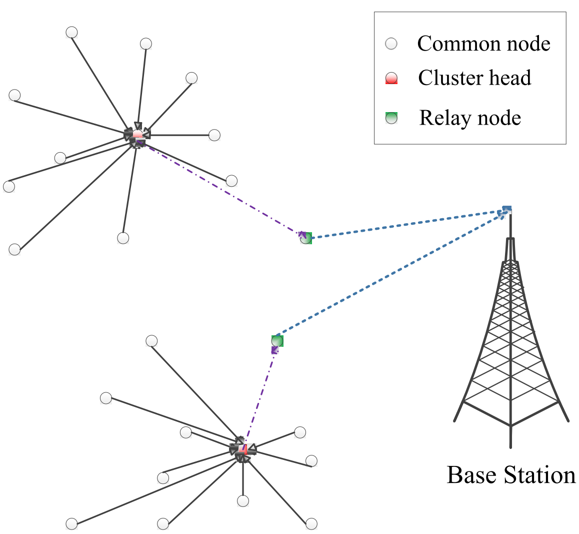

FIGURE 2. The topology of the proposed protocol.

A. CLUSTER HEADS' SELECTION

We assume that there are N sensor nodes randomly deployed in the field, which are divided into n clusters. We define the set of cluster heads as $CH = \{CH_1, CH_2, \ldots, CH_j, \ldots, CH_n\}$, and the set of non-CH nodes as $\widetilde{CH}$.

In the proposed protocol, the CHs are responsible for coordinating among the nodes within their cluster, aggregating intra-cluster data, and communicating with its RNs. The energy levels and locations of the nodes are taken into consideration in selecting the CHs. The BS tends to select the cluster heads with higher residual energy and better locations (near the BS), and forms the clusters with an equal distribution of the sensor nodes. This process can be formulated as an optimization problem and mathematically expressed as

$$F_{CH} = \alpha \times R_{energy}^{CH} + (1-\alpha) \times R_{location}^{CH}. \tag{5}$$

As shown in (5), F_{CH} consists of two parts. The constant α indicates the contribution of R_{energy}^{CH} and $R_{location}^{CH}$ in the fitness function F_{CH}. R_{energy}^{CH} is the ratio of CHs' average residual energy to non-CH nodes' average residual energy, in the current round, which can be expressed as:

$$R_{energy}^{CH} = \frac{\overline{E}_{CH}}{\overline{E}_{\widetilde{CH}}} = \frac{\sum_{\forall node_j \in CH} E_{CH}^{res}(j)/|CH|}{\sum_{\forall node_i \in \widetilde{CH}} E_{\widetilde{CH}}^{res}(i)/|\widetilde{CH}|} \tag{6}$$

where $\overline{E}_{CH}$ is the average residual energy of the CHs, while $\overline{E}_{\widetilde{CH}}$ is the average residual energy of the non-CH nodes. $|CH|$ and $|\widetilde{CH}|$ represent the numbers of the CHs and non-CH nodes, respectively. By maximizing R_{energy}^{CH}, nodes with higher energy levels tend to be chosen as the CHs.

$R_{location}^{CH}$ is the ratio of the average distance between the non-CH nodes and the BS to the average distance between the CHs and the BS, which can be expressed as

$$R_{location}^{CH} = \frac{\overline{D}_{\widetilde{CH}}}{\overline{D}_{CH}} = \frac{\sum_{\forall node_i \in \widetilde{CH}} d(node_i, BS)/|\widetilde{CH}|}{\sum_{\forall node_j \in CH} d(node_j, BS)/|CH|} \tag{7}$$

where $d(node_i, BS)$ denotes the Euclidean distance between node i and the BS. By maximizing the object function $R_{location}^{CH}$, it is expected that the cluster formation and the CHs' selection of the WSN can be optimized so as to improve the energy efficiency of the sensor network.

In practical applications, the sensor nodes are powered by battery. A node's residual energy can be indicated by its present battery voltage. This information can be indicated in the data packet. The location of the nodes can be obtained by implementing localization services as discussed in [35].

If a node has more residual energy and is closer to the BS, it is more likely to be selected a CH. This problem can be seen as an NP-hard problem. As such, we propose an improved PSO algorithm to solve it, which is described in detail in Section IV.

B. RELAY NODES' SELECTION

To reduce the excessive energy consumption of the cluster heads, relay nodes are used in our protocol to share data transmission task with the CHs. A sensor node ought to be selected as a relay node if it meets the following two criteria. Firstly, the relay nodes and cluster head must have a higher energy level, since they consume much more energy compared with common nodes. Second, the node should have a superior location between the cluster node and the BS so as to minimize the transmission energy, which is the most dominant energy consumption in the WSN. Different from other protocols, the selection of relay nodes in our protocol is related to the cluster heads, each of which has a corresponding relay node. As a result, the communications costs between the cluster heads and relay nodes can be reduced.

We define the set of relay nodes as $RN = \{RN_1, RN_2, \ldots, RN_z, \ldots, RN_m\}$, and the set of common nodes as CN. Similar to cluster selection in Section IV.A, in order to select the relay node, we define the following fitness function:

$$F_{RN} = \beta \times R^{RN}_{energy} + (1-\beta) \times R^{RN}_{location} \tag{8}$$

where R^{RL}_{energy} reflects the ratio of the relay nodes' residual energy to the common nodes' residual energy which can be expressed as:

$$R^{RN}_{energy} = \frac{\overline{E}_{RN}}{\overline{E}_{CN}} = \frac{\sum_{\forall node_z \in RN} E^{res}_{RN}(z)/|RN|}{\sum_{\forall node_k \in CN} E^{res}_{CN}(k)/|CN|} \tag{9}$$

where $\overline{E}_{RN}$ is the average residual energy of the relay nodes. $|RN|$ and $|CN|$ represent the numbers of the relay nodes and common nodes, respectively. By maximizing R^{RN}_{energy}, the nodes with higher energy nodes are more likely to be selected as the relay nodes.

Meanwhile, the function of $R^{RN}_{location}$ is defined as:

$$R^{RN}_{location} = \frac{\overline{L}_{CN}}{\overline{L}_{RN}} = \frac{\sum_{\forall node_k \in CN} \{d(node_k, BS) + d(node_k, CH_j)\}/|CN|}{\sum_{\forall node_z \in RN} \{d(RN_z, BS) + d(RN_z, CH_j)\}/|RN|} \tag{10}$$

According to the equation, to select CH_j's corresponding relay node RN_z, the location of CH_j and BS is taken into consideration. Maximizing $R^{RN}_{location}$ means reduced the transmission costs between the cluster heads and relay nodes. For example, in Fig. 3, the BS tends to choose node B, instead of node A, C or D, as the cluster head's relay node due to the least transmission distance.

C. CLUSTERING INFORMATION

Fig. 4 presents the flowchart of the whole procedure, including the clustering setup phase and data transmission phase. The selection algorithm of cluster heads and relay nodes is operated on the BS system like other protocols.

1) CLUSTERING SETUP PHASE

In the sensor network, each node is assigned an index (ID) in accordance with its location, and the selection algorithm of

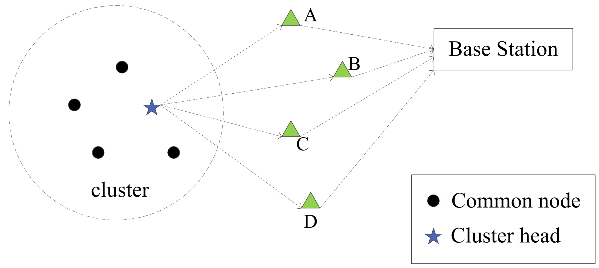

FIGURE 3. Relay nodes' selection.

cluster heads and relay nodes is carried out by the BS similar to other protocols. The procedure is as follows.

- At the beginning, each node sends a Node-MSG message to broadcast its residual energy information and location information, which are essential for selecting the cluster heads and relay nodes;
- The BS selects the cluster heads by using the algorithm in Section III.A, and broadcast a message including the cluster heads' ID to inform the network of the cluster head's location. After the cluster heads know their status, each cluster head introduces itself to the network by broadcasting a small advertisement message (i.e., CH-ADV), which uses the non-persistent carrier-sense multiple access (CSMA) MAC protocol. The message includes the cluster head's ID and a header that identifies it as an advertisement message;
- Then, similarly, the BS select the relay node by using the algorithm in Section III.B. Once a relay node is selected, an advertisement message (i.e., RN-ADV), which includes its ID, the corresponding cluster head's ID and the header, is sent to the network by the BS to declare its status as a relay node. Each common node decides its cluster by choosing the cluster head that requires the minimum transmission energy, based on the strength of the CH-ADV message from each cluster head. Then, a cluster is chosen;
- After each common node has decided which cluster it joins in, it must inform the cluster head of its decision by transmitting a JOIN-REQ message. The message is again very short, consisting of the node's ID, the belonging cluster head's ID and the sender's residual energy. In this way, clusters are formed, and the duty of each node in the network is determined.

The cluster head in a cluster acts as the control center for the objective of coordinating data transmissions. The cluster head sets up a TDMA scheduler and broadcasts the SCHEDULE-MSG message to the common nodes in the cluster as well as the corresponding relay node. This avoids collisions among data messages, and also allows the radio components of each common node and relay node to be switched off at all times, except when the common nodes transmit messages or relay nodes receive messages. This helps us to increase spectral efficiency and decrease energy consumption by individual sensors. When the TDMA scheduler is known to all the common nodes, the

FIGURE 4. Flowchart of the network operation, including clustering setup phase and data transmission phase.

clustering setup phase is complete and the data transmission phase begins at the same time with a deterministic topology.

2) DATA TRANSMISSION PHASE

In this phase, the common nodes send data to their cluster head as scheduled by the TDMA scheduler. The nodes are all synchronized through the BS sending out synchronization pulses to the nodes. The cluster head must be awake at all times to receive all the data from the common nodes in the cluster, and then it aggregates the data to enhance the common signal and to reduce the un-correlated noise among the signals. Afterwards, the cluster head transmits the aggregated data to the relay node. Through analyzing the TDMA scheduler managed by the cluster head, the sensor nodes can turn on or off radio so as to save energy.

Then the resultant data are sent from the relay node to the BS.

IV. CLUSTER NODE UPDATING ALGORITHM BASED ON AN IMPROVED PSO

In recent years, many optimization algorithms have been widely used in the WSN [36], [37]. The particle swarm optimization (PSO) algorithm is a population-based stochastic optimization technique developed by Dr. Eberhart and Dr. Kennedy in 1995, inspired by social behaviors of bird flocking of fish schooling. The system is initialized with a population of random solutions and searches aiming for optima by updating generations. PSO has no evolution operators such as crossover and mutation. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles.

Owing to its simple concept and high efficiency, PSO has become a widely adopted optimization technique and has been successfully applied to many real-world problems, particularly multimodal problems [38], [39]. Hence, it is an effective algorithm to solve the clustering problems of energy efficiency and minimal transmission distances for the clustering setup phase. In our previous work, we use PSO algorithm to solve software-defined network problems successfully [40]. However, PSO performs poorly in terms of local search with premature convergence, especially for complex multi-peak search problems [41], [42]. In order to deal with this specific scenario, we improved the conventional PSO algorithm by adjusting the inertial weight to avoid particles being trapped in local optima, and used the improved PSO algorithm to maximize the fitness functions of (5) and (8). As a consequence, more suitable cluster heads and relay nodes are selected, which makes the protocol more energy-efficient. This section describes how the improved PSO algorithm is designed to optimally cluster the WSN in the clustering setup phase. The approach consists of the following five main steps:

1) ***Initialize the optimization problem and algorithm parameters.*** Generate a certain number of particles. The size of the particle is defined as M, each particle i has a velocity vector $v_i = [v_{i1}, v_{i2}, \ldots, v_{id}]$, and a position vector $x_i = [x_{i1}, x_{i2}, \ldots, x_{id}]$ is used to indicate its current state, where i is a positive integer indexing the particle in the swarm and d refers to the dimensions of the problem.
2) ***Calculate the fitness values.*** The particles search in a d-dimensional hyperspace, calculating the fitness values of each particle based on (5) and (8). During the search process, each particle keeps track of the personal best (pbest) solution $P_i = [p_{i1}, p_{i2}, \ldots, p_{id}]$ by itself and the global best (gbest) solution $P_g = [p_{g1}, p_{g2}, \ldots, p_{gd}]$ achieved by any particle in the swarm. Then the local best position and the global position will be found.
3) ***Update velocity and position vectors.*** Each step influences the velocity of each particle towards its pbest and gbest positions. The velocity of the particle is updated as follows:

$$v_{ij}^{k+1} = wv_{ij}^{k} + c_1 r_1 (p_{ij}^{k} - x_{ij}^{k}) + c_2 r_2 (p_{gj}^{k} - x_{gj}^{k}), \quad (11)$$

and the position of the particle is updated as follows:

$$x_{ij}^{k+1} = x_{ij}^{k} + v_{ij}^{k+1} \quad (12)$$

where v_{ij} is the jth dimension of the ith particle's velocity and it is usually confined to the closed interval of $[v_{min}, v_{max}]$ to prevent the explosion of the particles. The notation of x_{ij}, p_{ij} and p_{gj} is similar to that of v_{ij}. Coefficients r_1 and r_2 are two randomly generated values within the range of [0, 1] for the dth dimension. c_1 and c_2 are two acceleration parameters commonly set to 2.0 or adaptively controlled according to the evolutionary states. Factor w is the inertial weight, which plays the role of controlling the impact of the previous velocity of a particle on the current one so as to balance between the global search (large inertial weight) and the local search (small inertial weight).
4) ***Change the inertial weight.*** To avoid the algorithm falling into a local optimum, we use an improved particle swarm optimization algorithm, which modifies the inertial weight as shown in (13) so as to avoid particles being trapped in local optima.

$$w = (w_{max} - w_{min}) \times \frac{Interation_{max} - Iteration_i}{Interation_{max}} + w_{min} \quad (13)$$

where w_{max} and w_{min} represent the maximum and minimum inertial weights, and are always set to 0.9 and 0.4, respectively. $Interation_{max}$ is the maximum number of allowed iterations, while $Interation_i$ represents the current interation.
5) ***Go to step 3 until the termination criterion is met.*** The current best solution is selected after the termination criterion is met. This is the solution for the optimization problem formulated.

V. PROTOCOL ANALYSIS

A. ENERGY CONSUMPTION ANALYSIS

Theorem 1: If there are N nodes distributed uniformly in an $M \times M$ region, the optimal number of cluster heads is $n_{opt} = \frac{M\sqrt{N}}{\sqrt{2\pi}} \sqrt{\frac{E_{fs}}{E_{elec} + d_{toBS}^4 Emp}}$, which will minimize the overall energy consumption.

Proof: Suppose the number of clusters is n. A cluster head has a corresponding relay node, and it is assumed that each cluster has one relay node. The average number of nodes in a cluster is N/n (one cluster head, one relay node, and $N/n - 2$ common nodes). The area occupied by each cluster is approximately M^2/n. In general, this area can be an arbitrarily shaped region with a node distribution of $\rho(x, y)$. We can derive the expected distance $E[d]$ from the common nodes to their cluster head ($x_c = 0, y_c = 0$):

$$\begin{aligned} E[d] &= \int\int \sqrt{(x-x_c)^2+(y-y_c)^2}\rho(x,y)dxdy \\ &= \int\int \sqrt{x^2+y^2}\rho(x,y)dxdy \\ &= \int\int r^2\rho(r,\theta)drd\theta. \end{aligned} \tag{14}$$

The node density is assumed to be uniform throughout the network. That is, $\rho(r,\theta)$ is a constant, which can be computed as

$$\rho(r,\theta) = \rho = \frac{1}{M^2/n} = \frac{n}{M^2}. \tag{15}$$

If we assume that the cluster is a circle with a radius of $R = M/\sqrt{n\pi}$, the expected distance $E[d]$ can be simplified into

$$\begin{aligned} E[d] &= \rho\int_0^{2\pi}\int_0^{M/\sqrt{n\pi}} r^2 drd\theta \\ &= \frac{n}{M^2}\cdot\frac{2M^3}{3n\sqrt{n\pi}} = \frac{2nM}{3\sqrt{n\pi}}. \end{aligned} \tag{16}$$

Since the cluster head is close to the common nodes in its cluster, presumably the energy dissipation follows the free space model (i.e., d^2 power loss). Moreover, the expected value of d^2 ($E[d^2]$) is obtained as follows:

$$\begin{aligned} E[d^2] &= \int\int (x^2+y^2)\rho(x,y)dxdy \\ &= \rho\int_0^{2\pi}\int_0^{M/\sqrt{n\pi}} r^3 drd\theta \\ &= \frac{M^2}{2n\pi}. \end{aligned} \tag{17}$$

Thus, according to Section II-B, the energy consumed by a common mode for signal transmission and receptions plus the occasional sleep phases, can be computed as follows:

$$\begin{aligned} E_{CO} &= (1-p_s)[E_{TX}(k,d)+E_{RX}(k)]+p_sE_s \\ &= (1-p_s)(kE_{elec}+kE_{fs}\times\frac{M^2}{2n\pi}+kE_{elec})+p_sE_s \end{aligned} \tag{18}$$

where p_s is the sleep probability of a common node, and E_s is the energy consumed when the node is asleep.

Each cluster head will receive signals from the nodes belonging to its cluster, aggregate and transmit data to its relay node. It is assumed that the distance between the cluster head and its relay node is reasonably short, so that the free space model (d^2 power loss) is adopted. Hence, the energy dissipated by a cluster head is

$$\begin{aligned} E_{CH} &= E_{TX}(k,d)+(\frac{N}{n}-2)E_{RX}(k)+\frac{N}{n}kE_{DA} \\ &= kE_{elec}+kE_{fs}\frac{M^2}{2n\pi}+(\frac{N}{n}-2)kE_{elec}+\frac{N}{n}kE_{DA} \end{aligned} \tag{19}$$

where E_{DA} is the energy dissipated per bit due to data aggregation.

Each relay node will receive data from the cluster head and then transmit them to the BS once in a round. Since the relay nodes are far from the BS, the dissipation follows the multi-path model (i.e., d^4 power loss). As such, the energy consumed by the relay node can be shown as

$$\begin{aligned} E_{RN} &= (1-p_s)[E_{TX}(k,d)+E_{RX}(k)]+p_sE_s \\ &= (1-p_s)[kE_{elec}+kE_{mp}d_{toBS}^4+kE_{elec})+p_sE_s \end{aligned} \tag{20}$$

where d_{toBS} is the distance between the relay node and the BS.

Therefore, the energy dissipated within a cluster is given by

$$E_{cluster} = E_{CH}+E_{RN}+(\frac{N}{n}-2)E_{CN}. \tag{21}$$

Finally, the total energy consumed by the sensor network is given by

$$E_{total} = nE_{cluster}. \tag{22}$$

From the above analysis, it can be concluded that the overall energy consumption depends upon the number of nodes, the size of the network, and the location of the BS.

In addition, we can solve for the optimum number of clusters by taking a derivative of (9) with respect to n:

$$\frac{\partial E_{total}}{\partial n} = 0 \Longrightarrow n_{opt} \approx \frac{M\sqrt{N}}{\sqrt{2\pi}}\sqrt{\frac{E_{fs}}{E_{elec}+d_{toBS}^4Emp}}. \tag{23}$$

B. TIME AND MESSAGE COMPLEXITIES

Theorem 2: The overall complexity of control messages in the network is $O(N)$.

Proof: At the beginning of each round, each node broadcasts a Node-MSG message. As a result, there are N Node-MSG messages in the network. In each round, each common node broadcasts a JOIN-REQ message, while each cluster head introduces itself to the network by broadcasting a CH-ADV and a SCHEDULE-MSG message. Similarly, each relay node broadcasts a RN-MSG message. We suppose the numbers of cluster heads and relay nodes are both n. Thus, the total number of JOIN-REQ is $N-2n$, and the numbers of CH-ADV, SCHEDULE-MSG and RN-MSG messages are all n. Therefore, the total number of control messages in the network is $N+(N-2n)+n+n+n = 2N+n$. Thus, the overall complexity of control messages in the network is $O(N)$.

Theorem 3: The time complexity of the protocol is $O(N^{1.5})$.

Proof: In the selection of the cluster heads, the distance between each node and the BS is computed. Thus, the time of distance computation is N. Similarly, to select relay nodes, the distance between the sensor nodes (except cluster heads) and the BS as well as the corresponding cluster head should be computed. Therefore, the time for distance computation time is $2(N-n)$. Thus, to select n cluster heads and relay nodes, the computation is $nN + 2n(N - n) = 3nN - 2n^2$. According the conclusion in Section A, the time complexity of the protocol is $O(N^{1.5})$.

VI. EXPERIMENTAL RESULTS AND ANALYSIS

This section presents the performance evaluation results of the proposed protocol via computer simulations. Our approach can be used to construct energy-efficient hierarchies for routing protocols, in which higher tier nodes should have more residual energy. Moreover, the protocols can also be effective for sensor applications requiring efficient data aggregation and prolonged network lifetime, such as environmental monitoring applications. According to the energy consumption in Section V, we know that the node number, network area size and the position of the BS are the three main parameters affecting the lifetime of the network. This section takes them into consideration when comparing various routing protocols to evaluate the protocol. The simulation models and programs are developed in MATLAB. To make results more reliable, average values are taken from 20 simulation runs. TABLE 1 lists the parameters of simulation in details.

TABLE 1. Simulation parameters.

Type	Parameter	Value
Network	Area	(0,0)~(100,100)
	Location of data sink	(50,175)
	Initial energy	2J
Radio model	E_{elec}	50nJ/bit
	E_{fs}	10pJ/bit/m^2
	E_{mp}	0.0013pJ/bit/m^4
	d_0	75m
	E_{DA}	5nJ/bit/signal

A. PERFORMANCE OF THE PROPOSED PROTOCOL

Our protocol aims at prolonging the lifetime of the network. We use the scenario described in TABLE 1. Then through calculating (23), we can get 5 as the number of CHs. As shown in (5) and (8), the fitness functions consist of two parts, representing the energy and location information. The coefficients α and β are set to 0.5, which indicates an equal contribution of energy and location.

Fig. 5 depicts the convergence rate of the fitness value of the objective function. It can be observed that the fitness value converges after less than 50 iterations. As a result, we set the maximum number of iterations of the algorithm to 50.

In Fig. 6, the total energy consumption of the network versus both the number of alive nodes and the "round" is shown in a 3D plot. An alive node is a node whose battery is not completely depleted. As shown, the energy of the network drops quickly as the lifetime advances, which is due to the fact that all the nodes consume their energy to finish their own tasks. The first node dies at about 1200 rounds, all the nodes completely deplete their energy at around 1500 rounds.

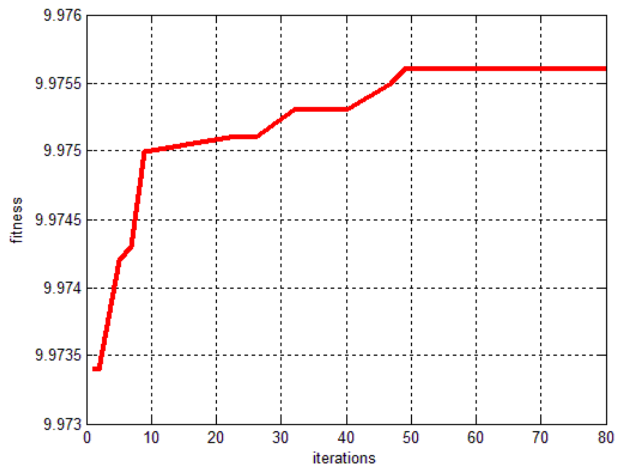

FIGURE 5. Convergence of the objective function when using an improved PSO algorithm.

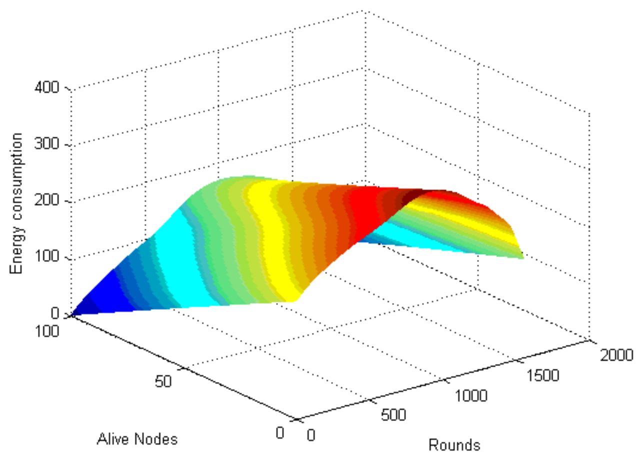

FIGURE 6. Total network energy consumption versus the number of alive nodes and the total energy consumption of the sensor network.

The proposed protocol uses the improved PSO to enhance the search performance of PSO. Fig. 7 compares its performance with that of the PSO-based protocol. The time span from start to when the first node dead is called FND (First Node Dead). What's more, the rounds when half of the nodes die is called HND (Half number of Nodes Dead). Another measure is LND (Last Node Dead), which is the time span from the time zero to when there is no alive node in the network. It is shown that, comparing with the PSO-based protocol, the FND, HND and LND of the proposed protocol are prolonged by 109.6%, 111.0%, and 108.0%, respectively. The improved PSO algorithm modifies the inertial weight of PSO to avoid particles being trapped in local optima, as a consequence, more suitable cluster heads and relay nodes are selected, which makes the protocol more energy-efficient.

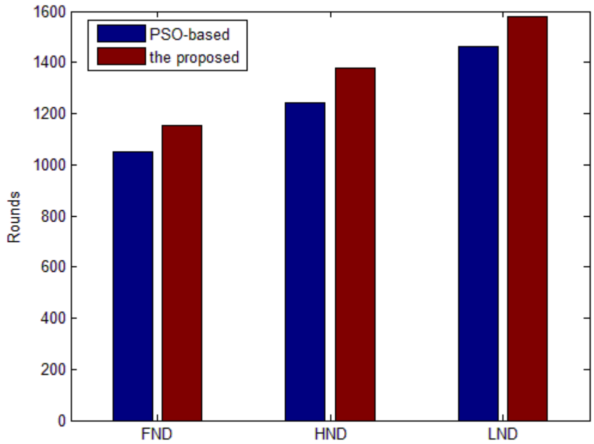

FIGURE 7. Comparison between the proposed protocol and the POS-based protocol.

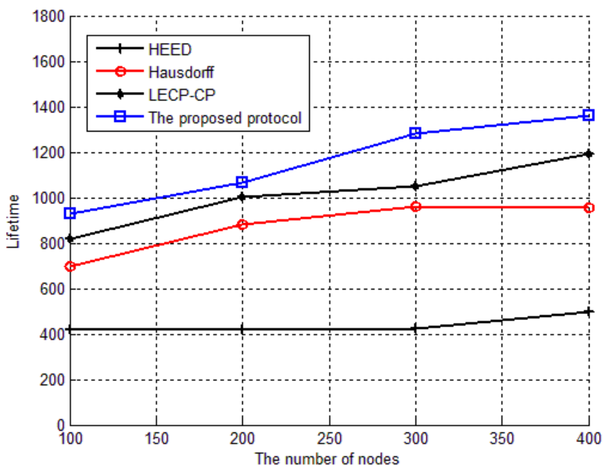

FIGURE 8. Lifetime comparison with different protocols.

B. LIFETIME COMPARISON IN DIFFERENT NODE DENSITY

Node density is one of the factors affecting the lifetime of the sensor network. Our proposed protocol is compared with HEED [17], Hausdorff [31] and LECP-CP [32] with different node densities. Fig. 8 compares the network lifetime of the aforementioned three protocols. The number of nodes ranges from 100 to 400. Compared to the comparative protocols, the proposed protocol demonstrates a better performance for all the experiments. After increasing the number of nodes, the proposed protocol still outperforms HEED, Hausdorff and LECP-CP.

HEED ensures only one cluster head within a certain range. This results in heavy energy consumption for the cluster heads. Hausdorff uses a greedy algorithm to select the cluster heads, but the clusters are formed only once. LECP-CP selects the cluster heads and constructs an inter-cluster communications routing tree based on the predicted local energy consumption ratio of the nodes, which gives good results. Our protocol rotates the cluster head's role among all the nodes so as to balance the load. Furthermore, the relay nodes are selected to offload the excessive energy consumption for the cluster heads. The protocol produces a better clustering structure of the network, and the cluster heads are distributed more uniformly across the network. The energy consumption of all the nodes are reduced because of the shorter distances between the common nodes and their cluster heads, as well as the short distances between the relay nodes and the BS.

C. NETWORK LIFETIME COMPARISON IN DIFFERENT SCENARIOS

We consider three scenarios to evaluate the lifetime performance of the proposed protocol. These scenarios differ from in the node number, network area size and the position of the BS as shown in Table 2. We compare the performance of the proposed protocol with LEACH, TCAC [30] as well as SEECH [33], which uses relay nodes in the protocol.

TABLE 2. Three different simulation scenarios.

Parameter	Scenario 1	Scenario 2	Scenario 3
Area	(0,0)∼(100,100)	(0,0)∼(100,100)	(0,0)∼(200,200)
Location of the BS	(50,175)	(50,200)	(100,350)
N	100	400	1000

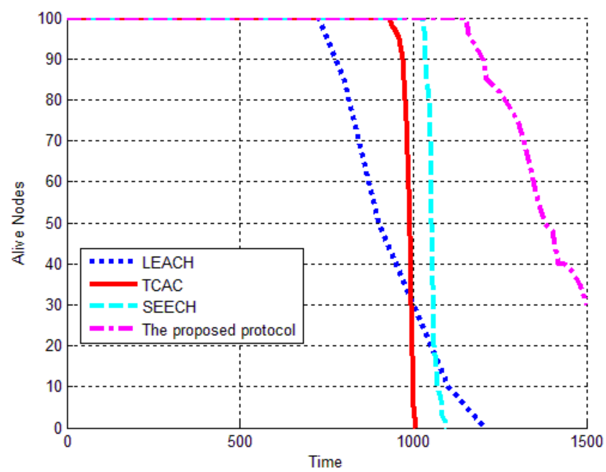

FIGURE 9. Number of alive nodes for scenario 1.

Figs. 9, 10, and 11 plot the number of alive nodes during simulation time in terms of rounds. As can be seen from Figs. 9 and 10, our protocol performs constantly better than the other three comparative protocols. In Fig. 11, In Scenario 3, even though SEECH has a longer FND lifetime, our method has a better performance in LND lifetime and PND lifetime, which are more effective metrics when there is a large number of sensor nodes in a network. TABLES 3 and 4

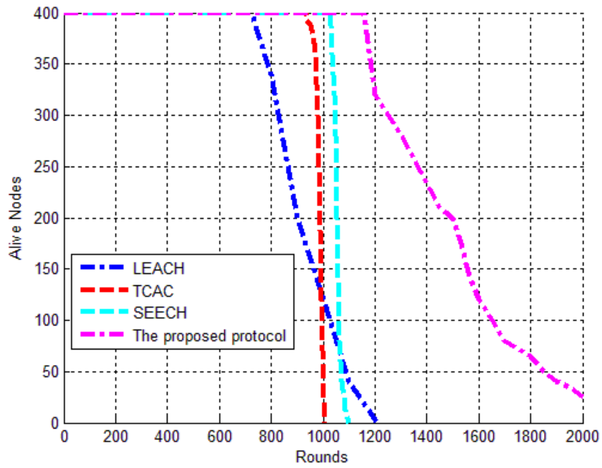

FIGURE 10. Number of alive nodes for scenario 2.

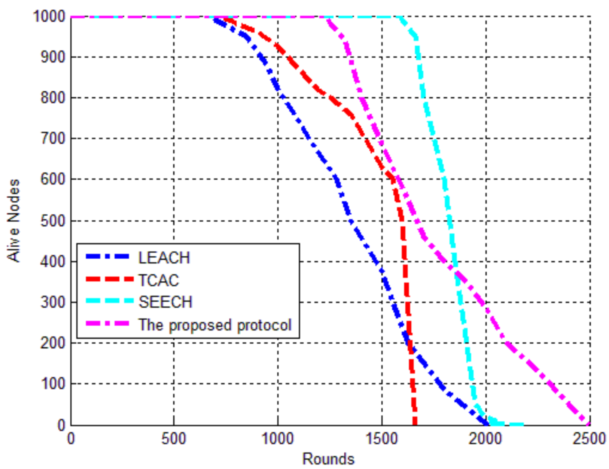

FIGURE 11. Number of alive nodes for scenario 3.

TABLE 3. PND comparisons between the proposed algorithm and LEACH, TCAC and SEECH.

Scenario	Protocol	Rounds	Compared with LEACH
Scenario 1	LEACH	990	1
	TCAC	1002	1.01
	SEECH	1085	1.10
	Proposed	1498	1.42
Scenario 2	LEACH	1003	1
	TCAC	992	0.98
	SEECH	1087	1.08
	Proposed	1601	1.60
Scenario 3	LEACH	1536	1
	TCAC	1601	1.04
	SEECH	1883	1.23
	Proposed	1995	1.29

compare these protocols in terms of the LND lifetime and PND lifetime. These comparative results clearly demonstrate the proposed protocol is capable of prolonging the network lifetime.

In SEECH, two or more cluster heads may choose the same relay nodes, which may result in fast depletion of energy for

TABLE 4. LND comparisons between the proposed algorithm and LEACH, TCAC and SEECH.

Scenario	Protocol	Rounds	Compared with LEACH
Scenario 1	LEACH	1209	1
	TCAC	1006	0.83
	SEECH	1099	0.91
	Proposed	1578	1.3
Scenario 2	LEACH	1274	1
	TCAC	1071	0.84
	SEECH	1140	0.89
	Proposed	2104	1.65
Scenario 3	LEACH	2014	1
	TCAC	1664	0.83
	SEECH	2204	1.1
	Proposed	2495	1.24

the chosen relay node. What's more, extra energy may be required of the cluster head to choose its relay node. In our protocol, every cluster head has a corresponding relay node, so the cluster heads do not need additional energy to choose its next-hop node, and channel contentions which occurs in choosing relay nodes by the cluster heads is avoided. Moreover, the proposed protocol takes account of the location information of the sensor nodes. Therefore, the proposed protocol performs a better result.

VII. CONCLUSION

In this paper, we proposed a new clustering protocol for the cluster-based wireless sensor network. In our protocol, the relay nodes are used to offload the heavy consumption of the cluster heads. Moreover, we proposed an improved PSO algorithm to create the cluster structure so as to minimize the transmission distance and to optimize the energy consumption of the network. In this way, the network lifetime can be prolonged. Under a variety of node densities, network area sizes and BS positions, it has been shown that the network can improve energy efficiency by minimizing the overall energy consumption and balancing energy consumption among the nodes during the network lifetime. Our simulation results showed that the protocol outperforms other comparative clustering protocols.

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