Particle Swarm Optimization-Based Unequal and Fault Tolerant Clustering Protocol for Wireless Sensor Networks

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***Abstract*— Clustering is one of most efficient energy saving techniques for maximizing network lifetime in wireless sensor networks. In the multi-hop approach, cluster heads (CHs) close to the base station deplete their energy very quickly due to high inter-cluster relay traffic load, causing the hot spot problem. Thus, a clustering protocol is required to be energy efficient as well as fault tolerant. This paper presents a particle swarm optimization (PSO)-based unequal and fault tolerant clustering protocol referred as PSO-UFC. The proposed protocol addresses imbalanced clustering and fault tolerance issues in the existing energy-balanced unequal clustering (EBUC) protocol for the long-run operation of the network. To solve the imbalanced clustering problem, the PSO-UFC protocol utilizes unequal clustering mechanism to balance intra-cluster and inter-cluster energy consumption between the Master CHs (MCHs). Also, in PSO-UFC protocol the network connectivity is restored by electing an extra CH called Surrogate CH due to sudden failure of MCH. The obtained simulation results demonstrate that the PSO-UFC protocol prolongs the network lifetime against EBUC, PSO-C, and LEACH-C protocols.**

***Index Terms*— Particle swarm optimization, unequal clustering, hot spot problem, fault tolerant, network lifetime.**

I. INTRODUCTION

WIRELESS sensor networks (WSNs) have come across as one of the emerging technologies in the recent years [1], [2]. The early research on WSN is mainly directed towards the monitoring applications, but with immense proliferation in micro-electro-mechanical systems (MEMS), there has been a widespread utilization of WSNs in different environments and for different purposes like Healthcare, Military Surveillance, Smart Grid, and Industrial Automation [3]. They incorporate automated sensing, embedded processing, and wireless transmission into tiny embedded devices referred as sensor nodes. Each sensor node is constrained to energy supply due to its limited and non-rechargeable battery source. Nevertheless, their processors have limited onboard processing power and storage capabilities. Such constraints require the energy resources of sensor nodes should be used wisely for the long run of WSNs [4]. In the recent past, clustering has been studied extensively for the energy conservation of WSNs. The clustering mechanism splits the network into small clusters, where each cluster has a Cluster Head (CH) node and member nodes. Once the network is partitioned into clusters, the communication among the nodes can be classified into: intra-cluster and inter-cluster communication. Non-CH nodes transmit their data to the CH, and then the CH transmits aggregated data to the base station (BS) either directly or through multi-hop routing [5]. However, in multi-hop routing, CHs near to the BS involved in high inter-cluster relay traffic load and deplete their energy very quickly compared to the other CH nodes. In literature, this issue is popularly known as the hot spot problem [6]. Moreover, sensor nodes are prone to failure due to quick depletion of their limited battery power or some malfunctioning of hardware components. The failure of a CH node interrupts the network communication not only with its member nodes as well as with the neighbor CHs [7]. Therefore, this paper addresses the hot spot problem, imbalanced clustering and fault tolerance issues in a joint manner.

Note that the CH-election is a Non-Deterministic Polynomial (NP)-hard optimization problem because the election of m optimal CHs among n sensor nodes give nC_m possibilities. Swarm intelligence approaches have been applied successfully to a variety of such NP problems. Particle swarm optimization (PSO) [8] is swarm intelligence based stochastic optimization technique which is inspired by social behavior of bird flocking, and fish schooling. It generally optimizes an issue by performing a series of iterations to improve the candidate solution regarding the given quality of the application. It can be a better choice for optimal CH selection because of its ease of implementation on hardware or software and ability to converge to an optimal solution very quickly. As clustering is a repeated process; therefore, simpler the optimization algorithm, the better the network efficiency is. This is another reason why PSO has been adopted widely to optimize the CH election process by several clustering protocols.

Energy-balanced unequal clustering (EBUC) protocol [9] addresses the hot spot problem by using PSO algorithm at the BS. The protocol creates unequal clusters in such a way that the ones near to the BS have lesser number of member nodes to support high inter-cluster relay traffic load. While clustering, EBUC does not consider node degree and residual energy of CHs which may lead to imbalanced energy distribution among the CHs. Moreover, EBUC protocol does

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not consider the fault tolerance issue. To mitigate imbalanced clustering and fault tolerance issues of the existing EBUC protocol, we propose a new particle swarm optimization based unequal and fault tolerant clustering protocol referred as PSO-UFC. The main contributions of this paper can be summarized as follows:

- PSO based clustering mechanism to solve hot spot problem in WSN.
- Derivation of the cost functions for unequal clustering mechanism to balance the intra-cluster and inter-cluster energy consumption.
- Construction of a multi-hop routing tree to ensure the network connectivity among the MCHs.
- Election of Surrogate Cluster Head in each cluster to address the fault tolerance issue.

The rest of the paper is organized as follows. The related work is presented in Section II. The preliminaries of network and energy models are given in Section III. The details of the proposed PSO-UFC protocol are discussed in Section IV. The simulation results are explained in Section V. Finally, Section VI concludes the paper.

II. RELATED WORK

Many of the existing clustering protocols in WSNs [5]–[17] are discussed in this section.

A. LEACH

LEACH [5] is a first hierarchical routing protocol where each sensor node has a probability to elect itself as the CH. Consequently, it selects a random number between 0 and 1. If the selected number is less than the threshold value, $T(n)$ the corresponding node gets a chance to become the CH for that round. The threshold value $T(n)$ is estimated by equation (1).

$$T(n) = \begin{cases} \frac{p}{1-p\times\left(r \bmod \frac{1}{p}\right)}, & if\ n \in G \\ 0, & otherwise \end{cases} \tag{1}$$

where, r is the current round, p is the desired probability of the nodes to become CH, G is the set of nodes that have not become CH in the last $1/p$ rounds. The equation (1) ensures that within $1/p$ rounds, each of the sensor nodes become the CH only once. Although LEACH balances the energy consumption of load by rotating the role of CH among the sensor nodes, still there exist various issues that are required to be considered: i) there is a probability to elect CH with lowest residual energy and tends to degrade the network performance. ii) single hop communication requires more energy to communicate with the BS.

B. LEACH-C

LEACH-C [10] is a centralized clustering protocol where the BS governs the entire CH election phase to maximize the network lifetime. The BS employs simulated annealing technique to select the optimal number of CHs throughout the network. The main drawback of LEACH-C is single-hop routing for inter-cluster communication that may cause imbalanced energy distribution, especially when a large number of CHs is placed far away from the BS. Thus, these CHs consume high energy while communicating with the BS and die very quickly.

C. PSO-C

An energy-aware clustering using PSO algorithm (PSO-C) [11] is a centralized clustering protocol in which BS controls the entire CH election and cluster formation process to enhance the lifetime of network. The BS considers both the intra-cluster distance between nodes and current energy of all CH nodes for efficient CH election. But the distance from the BS is not considered, which increases energy consumption during the direct communication of CHs to the BS.

D. EBUC

EBUC [9] is a centralized unequal clustering protocol which addresses hot spot problem by using PSO algorithm at the BS. The protocol creates unequal clusters in such a way that the CHs closer to the BS has smaller cluster size in order to preserve their battery energy for high inter-cluster relay traffic load. In addition, EBUC adopts greedy algorithm for multi-hop inter-cluster routing. While clustering, EBUC does not consider node degree and residual energy of CHs which may lead imbalanced energy distribution among the CHs. Moreover, it does not consider fault tolerance issue to avoid the quick failure of overloaded CHs.

E. IPSO

The improved version of Particle Swarm Optimization (IPSO) is adopted in the existing EBUC [9] protocol to prolong the network lifetime [12]. IPSO overcomes the standard PSO issues by widening the exploration area of the search particles. This is achieved by applying perturbations directly to the global best and personal best. But, issues existing in the EBUC protocol still remain to be solved.

F. PSO-ECHS

PSO-ECHS [13] is an energy-efficient clustering algorithm where the BS runs PSO to optimize both CH election and cluster formation. The protocol introduces a novel fitness function that minimizes the linear combination of the objective functions based on intra-cluster distance, BS distance, and residual energy of sensor nodes. The non-cluster head nodes join to CHs based on various parameters viz., distance, energy, and node degree of CHs to form the balanced clustering. But the network performance still degrades when the position of the BS changes from center to the corner.

In recent research, many clustering protocols based on PSO algorithm have been developed [14]–[17]. However, these algorithms do not consider hot spot problem and fault tolerance issue in the large-scale WSNs.

TABLE I
NOTATIONS USED IN PROPOSED PROTOCOL

Symbol	Description
N	The set of sensor nodes, i.e., $N = \{N_1, N_2, N_3.....N_n\}$
CH	The set of Master CHs, i.e., $CH = \{MCH_1, MCH_2, ...MCH_m\}$ where $m < n$
CM_i	The member nodes of Master CH i
l_j	Maximum no. of sensors which are in the communication range of Master CH j
RE	Residual energy of sensor node
$\lVert N_i - MCH_j \rVert$	The distance between sensor node N_i and Master CH j.
$E_R(MCH_j)$	The residual energy of Master CH j
$\lVert MCH_j - BS \rVert$	The distance between Master CH j and BS
$\lVert MCH_i - MCH_j \rVert$	The distance between Master CH i and Master CH j
$Node_{Degree}(MCH_j)$	The number of neighboring nodes in the cluster communication range of Master CH j

III. PRELIMINARIES

A. Network Model

The proposed network model consists of the BS and n sensor nodes which are deployed randomly over the network area. The following assumptions about the network and the sensor nodes are made:

1. All the sensor nodes and the BS are static after deployment.
2. The distance between the sensor nodes and the BS can be estimated by the received signal strength.
3. Each member node periodically performs sensing operation and transmits data to its own CH.
4. The BS is considered as a resource-rich electronic device having high computational abilities with no energy constraints.

B. Terminologies

The notations used in the proposed protocol are mentioned in Table 1.

C. Energy Model

The radio model adopted in this paper is same as discussed in [5]. In this model, a free space model (ε_{fs}) is used, when the propagation distance d is less than the threshold distance d_0; otherwise, the multi-path fading model (ε_{mp}) is used. The total energy consumed by the radio to transmit an l-bit message over a distance d is given by equation (2).

$$E_{TX}(l,d) = \begin{cases} l \times E_{elec} + l \times \varepsilon_{fs} \times d^2, & if\ d < d_0 \\ l \times E_{elec} + l \times \varepsilon_{mp} \times d^4, & if\ d \geq d_0 \end{cases} \tag{2}$$

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \tag{3}$$

where, E_{elec} is the amount of energy dissipated in electronics circuit. The energy consumed by the radio to receive an l-bit message is given by equation (4).

$$E_{RX}(l) = l \times E_{elec} \tag{4}$$

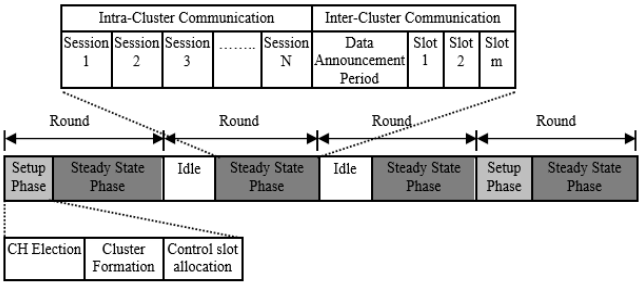

Fig. 1. Operation of PSO-UFC protocol.

IV. PROPOSED PROTOCOL

The operation of the proposed protocol is divided into rounds, where each round consists of set-up phase and steady-state phase as shown in Fig. 1. In set-up phase, the BS partitions the network into unequal clusters where each cluster has a MCH and a SCH and concurrently, constructs a multi-hop routing tree among the elected MCHs. Whereas, in the steady-state phase the sensor nodes transmit their sensed data to the BS via intra-cluster and inter-cluster communications. In order to reduce the energy consumption and computation time of the set-up phase, the PSO-UFC protocol executes this phase only if any of the SCH takes the role of its MCH; otherwise, it uses current MCHs for the next round. Fig. 2 shows the flowchart of the PSO-UFC protocol.

A. PSO Based Master Cluster Head (MCH) Election

Once the sensor nodes are deployed, the BS broadcasts an Info_Collect message to gather all the necessary information of the sensor nodes in the network. Each sensor node replies by sending an Info_Receive message contains its location (X) and residual energy (RE) to the BS. The BS tends to elect optimum MCHs with higher residual energy, lesser intra-cluster communication cost and better location (closer to the BS) to solve the hot problem and to maximize the network lifetime. This problem can be described as the optimization problem with the following three objectives:

1) *Average intra-cluster communication distance (f_1):* It is defined as the average distance between the sensor nodes and their associated MCHs. By minimizing f_1, sensor nodes with lesser intra-cluster communication cost tend to be elected as the MCHs. Thus,

$$\text{Minimize } f_1 = \sum_{j=1}^{m} \frac{1}{l_j} \left(\sum_{i=1}^{l_j} \lVert N_i - MCH_j \rVert \right) \tag{5}$$

2) *Average inter-cluster communication distance (f_2):* It is defined as the average distance between the MCHs and

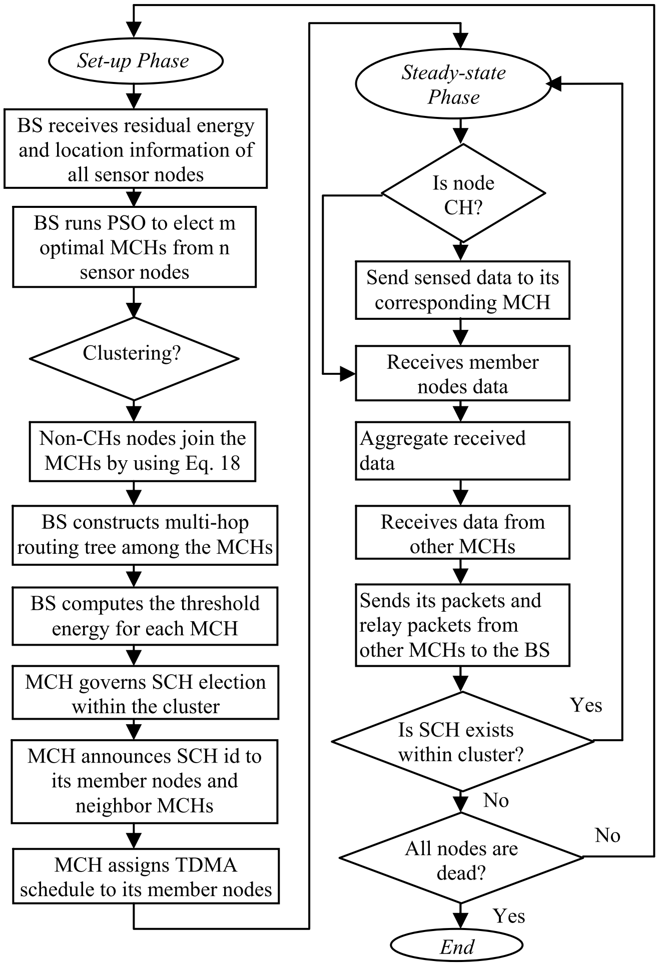

Fig. 2. Flowchart of PSO-UFC protocol.

the BS. By minimizing f_2, sensor nodes in the area closer to the BS tend to be elected as the MCHs. Thus,

$$\text{Minimize } f_2 = \sum_{j=1}^{m} \frac{1}{m} \left(\| MCH_j - BS \| \right) \tag{6}$$

3) *Residual energy (f_3):* It is defined as the remaining energy of the sensor nodes to perform sensing, computation and communication operations. By minimizing f_3, sensor nodes with higher residual energy tend to be elected as the MCHs. Thus,

$$\text{Minimize } f_3 = \frac{1}{\sum_{j=1}^{m} (E_R(MCH_j))} \tag{7}$$

The solution of the optimization problem is to minimize the following objective function:

$$Fitness = \alpha \times f_1 + \beta \times f_2 + \gamma \times f_3 \tag{8}$$

where, $\alpha, \beta,$ *and* γ are the control parameters in the range [0, 1] with $\alpha + \beta + \gamma = 1$ and $\beta \geq (\alpha + \gamma)$ to elect more number of CHs closer to the BS.

This problem of the optimal election of MCHs can be consider as an NP-hard problem. So, we propose a PSO algorithm to solve it. The detailed procedure of PSO based MCH election is described as follows:

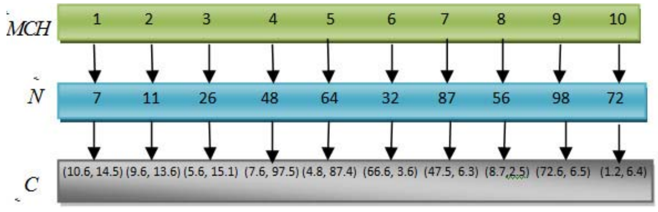

Fig. 3. An example of particle representation.

1) *Initialize the algorithm parameters:* PSO [18] consists of a swarm of predefined N_P solutions referred as particles. The particles explore in a D-dimensional search space to achieve a global optimum solution. The dimension D of the particle is same as the number of MCHs, i.e., *m*. Each particle i occupies a position $X_{i,d}$ and a velocity $V_{i,d}$ in the dth dimension of search space, such that $1 \leq i \leq N_P, 1 \leq d \leq D$. Let $P_i = \left[X_{i,1}(t), X_{i,2}(t), \ldots. X_{i,D}(t)\right]$ is the ith particle of the population, where each component $X_{i,d}(t) = (x_{id}(t), y_{id}(t))$ represents the coordinates of the sensor nodes which are elected as the MCHs. Then the ith particle becomes:

$$P_i = [(x_{i1}(t), y_{i1}(t)), (x_{i2}(t), y_{i2}(t)), (x_{i3}(t), y_{i3}(t)), \ldots\ldots\ldots\ldots\ldots (x_{id}(t), y_{id}(t))] \tag{9}$$

The representation of randomly generated particle P_i is shown in Fig. 3 in which MCH specifies the index of the CHs, N specifies the index of the sensor nodes which are elected as the MCHs and C specifies the randomly generated coordinates of the sensor nodes. Here, we consider a WSN with 100 sensor nodes and number of MCHs is 10 (10% of 100). The network area is assumed to be 100×100 and the particles are initialized by assigning coordinates to the sensor nodes in the range [0, 100]. As seen from Fig. 3, the sensor nodes [7, 11, 17, 22, 8, 22, 61, 44, 99] are elected as MCHs, such that node N_7 is assigned the coordinates (10.6, 14.5), N_{11} is assigned (9.6, 13.6) and so on.

2) *Calculate the fitness value:* Next step is to calculate the fitness value of each particle in the search space by equation (8). During the search space, each particle (P_i) keeps track of its personal best solution referred as $pBest_i$ and a global best solution called $gBest$ in a swarm.

3) *Update velocity and position:* At each step, the velocity and the position of a particle P_i are updated towards its $pBest_i$ and $gBest$ by using equations (10) and (11) respectively.

$$V_{i,d}(t+1) = w \times V_{i,d}(t) + c_1 r_1 (pBest_{i,d} - X_{i,d}(t)) + c_2 r_2 (gBest - X_{i,d}(t)) \tag{10}$$

$$X_{i,d}(t+1) = X_{i,d}(t) + V_{i,d}(t+1) \tag{11}$$

where, w is the inertial weight within the range of [0, 1], r_1, r_2 are two uniformly distributed random

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Pseudo code for PSO based Master CH election
Input: Parameter Initialization
a): Set of sensor nodes $N = \{N_1, N_2, N_3, .....N_n\}$
b): Predefined swarm size $N_P$
c): Number of dimensions of a particle $D = m$
d): Maximum number of iterations $I_{\max}$
Output:
a): Optimal set of MCHs $CH = \{MCH_1, MCH_2, .....MCH_m\}$
    Initialize particle $P_i, \forall i, j, 1 \le i \le N_P, 1 \le j \le D = m$
    Assign $X_{i,j}(0) = (x_{i,j}(0), y_{i,j}(0))$
    FOR each particle $P_i$
        Calculate $Fitness(P_i)$ using Eq. (8)
        $pBest_i = P_i$
    EndFor
    $gBest = \{pBest_k \mid Fitness(pBest_k)$
        $= \min(Fitness(pBest_k), \forall i, 1 \le i \le N_P\}$
    While $(t < T_R)$ do
        FOR each particle $P_i$
            Update ( $P_i$_velocity) using Eq. (10)
            Update ( $P_i$_position) using Eq. (11)
            Evaluate $Fitness(P_i)$
            If $Fitness(P_i) < Fitness(pBest_i)$ then
                $pBest_i = P_i$
            EndIf
            If $Fitness(P_i) < Fitness(gBest)$ then
                $gBest = P_i$
            EndIf
        EndFor
    t=t+1
    EndWhile
    End
```

Fig. 4. Pseudo Code of PSO based Master CH Election.

number within the range of [0, 1] and c_1, c_2 are two non-negative constants called acceleration factor commonly set to 2.0.

4) *Termination criteria:* The update process is iteratively repeated until a fixed number of iterations $I_{\max}$ are reached. Thus, the sensor nodes of a particle with minimum fitness value will be elected as the MCHs. The pseudo code of PSO based MCH election is shown in Fig. 4.

B. Cluster Formation

After MCHs election, the next challenging issue is the unequal cluster formation. In the proposed protocol, each MCH introduces itself to the network by broadcasting a small advertisement message called *CH-Adv* message contains its ID, location, distance to the BS, residual energy, and node degree. A sensor node may get multiple *CH-Adv* messages from its neighbor nodes. In that case, the non-CH node computes its cost value by considering the following parameters:

1) *Distance between MCH and sensor node:* A sensor node N_i will join to a nearest MCH_j in its communication range. Thus,

$$CH\_Cost(N_i, MCH_j) \propto \frac{1}{\|N_i - MCH_j\|} \tag{12}$$

2) *Distance between MCH to the BS:* The MCHs are elected to transmit aggregated data to the BS. Therefore, a sensor node N_i will join a MCH_j which is nearest to the BS. Thus,

$$CH\_Cost(N_i, MCH_j) \propto \frac{1}{\|MCH_j - BS\|} \tag{13}$$

3) *Node degree:* A sensor node N_i will join a MCH_j which has lesser number of neighboring nodes than the other MCHs in its communication range. Thus,

$$CH\_Cost(N_i, MCH_j) \propto \frac{1}{Node_{Degree}(MCH_j)} \tag{14}$$

4) *Residual energy:* A sensor node N_i will join a MCH_j which has higher residual energy than the other MCHs in its communication range.

$$CH\_Cost(N_i, MCH_j) \propto E_R(MCH_j) \tag{15}$$

Combining equations (12), (13), (14) and (15), we obtain

$$CH\_Cost(N_i, MCH_j) \propto \frac{E_R(MCH_j) \times \|MCH_j - BS\|}{\|N_i - MCH_j\| \times Node_{Degree}(MCH_j)} \tag{16}$$

$$CH\_Cost(N_i, MCH_j) = K \times \frac{E_R(MCH_j) \times \|MCH_j - BS\|}{\|N_i - MCH_j\| \times Node_{Degree}(MCH_j)} \tag{17}$$

where, K = 1 is the constant of is proportionality.

$$CH\_Cost(N_i, MCH_j) = \frac{E_R(MCH_j) \times \|MCH_j - BS\|}{\|N_i - MCH_j\| \times Node_{Degree}(MCH_j)} \tag{18}$$

For balanced cluster formation, each non-CH node computes its cost value i.e., CH_Cost using equation (18) and joins to a MCH with maximum cost value. Hence, the MCHs closer to the BS has smaller cluster size in order to preserve their energy for high inter-cluster relay traffic load.

C. Multi-Hop Routing Tree

Once the clusters are formed, the PSO-UFC protocol constructs the multi-hop routing tree among the elected MCHs. Before electing the next hop node, each MCH maintains a neighboring by equation (19).

$$Com(MCH_i) = \left\{MCH_j \,\middle|\, \|MCH_i - MCH_j\| < d_0\right\} \tag{19}$$

The neighboring MCHs which are in the direction from MCH_i to the BS, are added to the next hop node set of MCH_i denoted as $NH(MCH_i)$ which is defined in equation (20).

$$NH(MCH_i) = \left\{MCH_j \,\middle|\, \forall MCH_j \in Com(MCH_j) \wedge \|MCH_j - BS\| < \|MCH_i - BS\|\right\} \tag{20}$$

There may be more than one MCHs in the $NH(MCH_i)$ and therefore, the PSO-UFC protocol determines the best next hop node (NH_{best}) for each MCH by deriving the cost function based on the following parameters:

1) *Residual energy of Next hop:* A MCH_i should select that MCH from its $NH(MCH_i)$ which has higher residual energy. Therefore,

$$NH\_Cost(MCH_i, MCH_j) \propto E_R(MCH_j) \quad (21)$$

2) *Distance between MCH and its next hop:* A MCH_i should select the nearest MCH from its $NH(MCH_i)$. Therefore,

$$NH\_Cost(MCH_i, MCH_j) \propto \frac{1}{\left\| MCH_i - MCH_j \right\|} \quad (22)$$

3) *Distance of NextHop from the BS:* A MCH_i should select that MCH from its $NH(MCH_i)$ which has lesser distance from the BS. Therefore,

$$NH\_Cost(MCH_i, MCH_j) \propto \frac{1}{\left\| MCH_j - BS \right\|} \quad (23)$$

4) *Node degree of NextHop:* A MCH_i should select that MCH from its $NH(MCH_i)$ which has lower node degree. Therefore,

$$NH\_Cost(MCH_i, MCH_j) \propto \frac{1}{Node\_Degree(MCH_j)} \quad (24)$$

The cost function for the selection of the next hop MCH is derived by combining equations (21), (22), (23), and (24) and is given by equation (25), as shown at the bottom of this page.

The MCH which has the maximum cost value as calculated by equation (25) will be selected as the best next hop node (NH_{best}) of MCH_i and the pseudo code for the next hop MCH selection is given in Fig. 5.

D. Threshold Energy Calculation

After unequal cluster formation and multi-hop routing construction, the BS computes the maximum energy consumed by the MCHs during their steady-state phase which is based on their intra-cluster and inter-cluster traffic load. The total energy consumed by MCH_i due to its intra-cluster activity is given by equation (26).

$$\begin{aligned} E_{\text{intra\_cluster}}(MCH_i) &= CM_i \times E_{RX} + (CM_i + 1) \times E_{DA} \\ &\quad + E_{TX}(MCH_i, NH_{best}(MCH_i)) \end{aligned} \quad (26)$$

where, CM_i is the number of member nodes of MCH_i, and $NH_{best}(MCH_i)$ is the next hop MCH of MCH_i towards the BS for data transmission. The parameters E_{RX}, E_{DA} and E_{TX} represents the energy consumption due to data reception, aggregation, and transmission to the BS respectively.

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Pseudo code for Multihop Routing
Input: Positions, Residual Energy and Node degree of all $MCHs$
Output: $NH_{best}$ for each $MCH$
FOR each $MCH_i$
    Compute $\|MCH_i - BS\|$
    While $\forall MCH_j \in Com(MCH_i)$ is not null do
        Compute $\|MCH_j - BS\|$
        If $\|MCH_j - BS\| < \|MCH_i - BS\|$
            Put $MCH_j$ into $NH(MCH_i)$
        EndIf
        While $\forall MCH_j \in NH(MCH_i)$ is not null do
        Compute $NH\_Cost(MCH_j, MCH_i)$ using Eq. 25
        EndWhile
    EndWhile
[~, $nh_{best}$] = max$(NH\_Cost(MCH_i, MCH_j))$
$NH_{best}(MCH_i) = nh_{best}$
EndFor
End
```

Fig. 5. Pseudo code of Multi-hop routing.

Apart from the intra-cluster activities, MCH_i also acts as the relay node for inter-cluster traffic load. Thus, energy consumption of MCH_i in receiving and relaying the data packets from the other MCHs is given by equation (27).

$$\begin{aligned} E_{\text{inter\_cluster}}(MCH_i) &= relay(i) \times E_{RX} + relay(i) \\ &\quad \times E_{TX}(MCH_i, NH_{best}(MCH_i)) \end{aligned} \quad (27)$$

where, $relay(i)$ is the number of incoming packets from the other MCHs.

Thus, maximum threshold energy required by MCH_i during the steady-state phase is given by equation (28).

$$\begin{aligned} E_{TH}(MCH_i) &\\ &= E_{\text{intra\_cluster}}(MCH_i) + E_{\text{inter\_cluster}}(MCH_i) \end{aligned} \quad (28)$$

$$\begin{aligned} E_{TH}(MCH_i) &\\ &= (CM_i + relay(i)) \times E_{RX} + (CM_i + 1) \times E_{DA} \\ &\quad + (relay(i) + 1)E_{TX}(MCH_i, NH_{best}(MCH_i)) \end{aligned} \quad (29)$$

E. Surrogate Cluster Head Election

For Surrogate CH election, each MCH broadcasts a *Start_Election* message within its cluster. The member nodes reply by sending residual energy and location information to their respective MCHs. Among contenders, the nodes with residual energy greater than predefined threshold energy

$$NH\_Cost(MCH_i, MCH_j) = \frac{E_R(MCH_j)}{\|MCH_i - BS\| \times \left\| MCH_i - MCH_j \right\| \times Node\_Degree(MCH_j)} \quad (25)$$

limit (E_{TH}) are considered as the nominee for SCH, otherwise, it will be considered as a malicious node. Form the nominated member nodes, the sensor node relatively nearer to the MCH is elected as the SCH within the cluster. Each MCH introduces its SCH in the network by broadcasting a *SCH_Adv* message contains SCH node ID and position information.

F. Schedule Creation

After CH-election and cluster formation, each MCH creates the TDMA schedule for its member nodes by allocating time slots for data transmission. This TDMA schedule avoids a collision during the intra-cluster communication. It also ensures that their member nodes turn off their radio, except during their transmission, to minimize the energy consumption.

G. Data Transmission

Once the steady-state phase starts, the member nodes wake up, sense data and transmit to their respective MCHs during the allocated time slots. However, each MCH must keep its receiver ON to receive data from its member nodes. Once each MCH receives the sensed data from its member nodes, it aggregates the data into a single packet and transmits the resulting packets to the BS along the constructed multi-hop routing tree.

H. Fault Tolerance

In PSO-UFC protocol, the fault tolerance of MCHs is carried out in the data transmission phase. During this phase, a MCH may fail due to its quick energy depletion or some malfunctioning of hardware components. Then, there may be an information loss due to a disconnection between the MCHs and the BS. The PSO-UFC protocol addresses the fault tolerance issue by determining a SCH for each MCH within a cluster. A SCH prevents MCH from the quick energy depletion and takes its responsibility when its residual energy falls below predefined threshold energy. In such a situation, the MCH periodically sends its energy status to the SCH during the reserved slot. When the residual energy of a MCH falls below a predefined threshold energy limit, it notifies its SCH by transmitting a Trigger_Msg message. Based on the received message, the SCH broadcasts a Notice_Msg message to its member nodes and neighbor MCHs and prevents its MCH from quick energy depletion. Thus, the MCHs can conserve their energy to perform normal sensing operations and remain alive in a cluster for a longer period. However, this fault tolerance situation does not apply to the SCH because if in any of the SCH changes its mode to the MCH, the MCH-reelection mechanism is initiated by executing the set-up phase in next round.

Besides SCH, the cluster members can detect their faulty MCH when they do not receive an acknowledgment from their respective MCHs. In this situation, they immediately trigger a recovery function by sending their data to SCH instead of the MCH. Likewise, in the inter-cluster communication, when the low-level MCH has not received any acknowledgment from its relay MCH, it retransmits the data to the SCH of relay cluster.

TABLE II
SIMULATION PARAMETERS

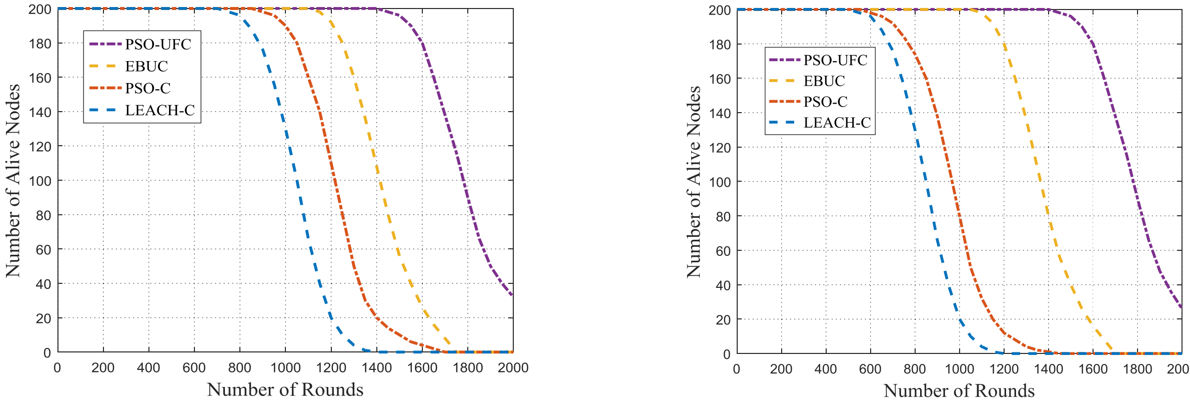
Type	Parameter	Value
Network	Area	200x200 m^2
	Number of Nodes	200
	Number of CHs	10
	Initial Energy	0.5 Joule
	Simulation Rounds	2000
	$I_{\max}$	100
Radio model	E_{elec}	50 nJ/bit
	ε_{fs}	10 pJ/bit/m^2
	ε_{mp}	0.0013 pJ/bit/m^4
	d_0	87 m
	E_{DA}	5 nJ/bit/signal
PSO model	c_1, c_2	2.00
	ω	0.4
	α	0.24
	β	0.52
	γ	0.24

V. SIMULATION RESULTS AND ANALYSIS

In this section, we evaluate the performance of PSO-UFC protocol against existing EBUC, PSO-C, and LEACH-C protocols using MATLAB (version R2013a). The protocols have been simulated in two different WSN scenarios (i.e., WSN#1 and WSN#2). In first scenario, WSN#1, the BS is located at the centre of the field, i.e., (100,100) and in second scenario, WSN#2, the BS is placed at the right corner of the field, i.e., (200, 25). The simulation parameters are mentioned in Table II.

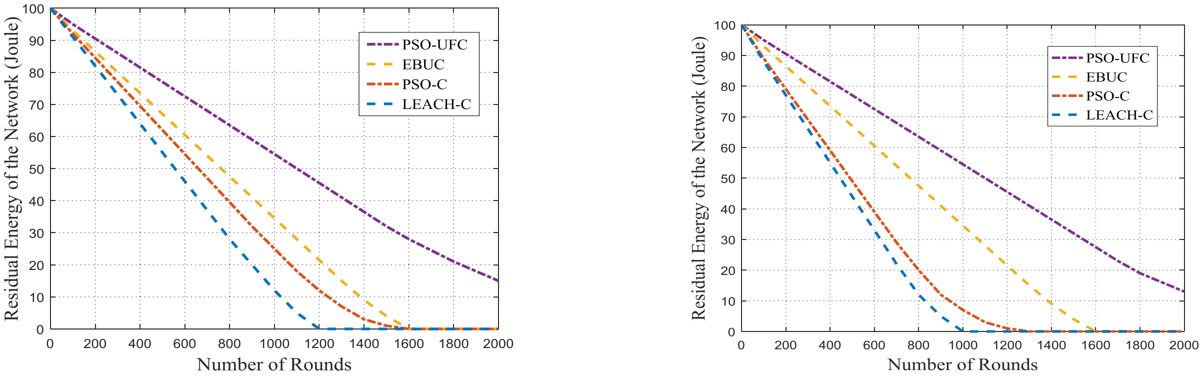
A. Performance of Proposed Protocol (PSO-UFC)

The performance of the PSO-UFC protocol is evaluated in terms of network lifetime, residual energy and total energy consumption of the network. The network lifetime is defined as number of communication rounds when first node dies (FND), or a certain percentage of nodes die. The FND metric is generally used in sparsely deployed WSNs. However, in densely deployed WSN, the death of a single node would not affect network connectivity and sensing operation. But when half number of nodes die, the quality of densely deployed WSN degrades a lot. Therefore, this work considers both FND and HND (half nodes die) metrics for comparison. Figs. 6 (a) and (b) show the number of sensor nodes still alive over the number of rounds in WSN#1 and WSN#2 respectively. In scenario 1, it is observed that PSO-UFC protocol outperforms all other clustering protocols in both FND and HND. Under FND criteria the PSO-UFC protocol improves the network lifetime by 21%, 55%, and 86% as compared to EBUC, PSO-C, and LEACH-C protocols respectively. This is because the SCH prevent the quick failure of MCH from its complete energy depletion. Whereas the existing protocols do not deal with the fault tolerance issue. Similarly, under



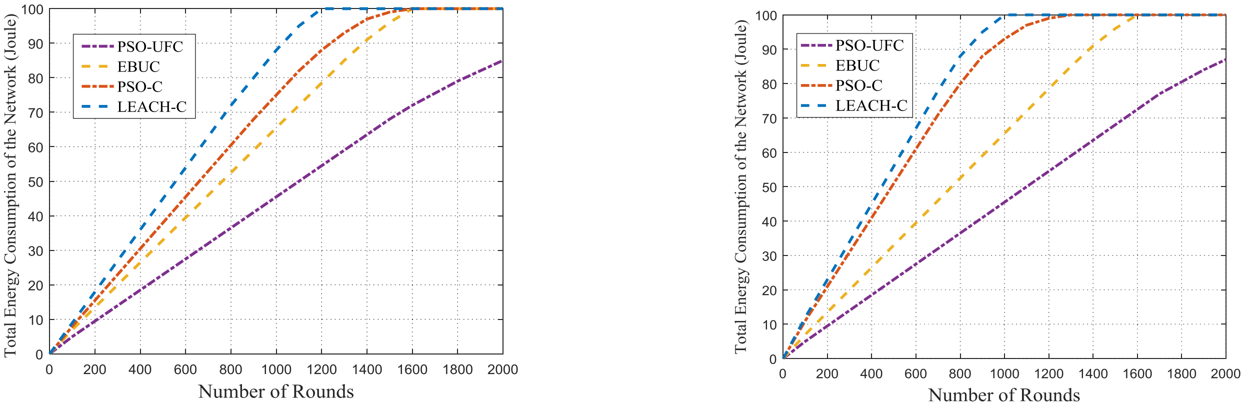
(a) (b)

Fig. 6. Network lifetime in rounds for scenarios: (a) WSN #1 and (b) WSN#2.



(a) (b)

Fig. 7. Residual energy (Joule) of the network in scenarios: (a) WSN #1 and (b) WSN#2.



(a) (b)

Fig. 8. Total energy consumption (Joule) of the network in scenarios: (a) WSN#1 and (b) WSN#2.

HDN criterion the network lifetime of PSO-UFC protocol is improved by 26%, 48%, and 68% against EBUC, PSO-C and LEACH-C protocols respectively. However, in LEACH-C and PSO-C protocols when the BS changes its position from centre to edge, the sensor nodes deplete their energy very quickly. This decline is due to the reason that both LEACH-C and PSO-C protocols do not address the hot spot problem of the network. Table III shows the number of alive nodes over the number of rounds of different protocols.

Figs. 7 (a) and (b) show the comparison of the PSO-UFC protocol and other clustering protocols in terms of the residual energy of the network in WSN#1 and WSN#2 respectively. The residual energy of the network is also considered as an important parameter to estimate the lifetime of a network. It is observed that the residual energy of the network in PSO-UFC protocol is much higher than EBUC, PSO-C, and LEACH-C protocols. This is because of two reasons: (i) by considering node degree and residual energy during the cluster formation, and (ii) assigning an appropriate inter-cluster relay traffic load to a MCH.

Figs. 8 (a) and (b) show the total energy consumption of the network along the number of rounds in WSN#1 and

TABLE III
NETWORK LIFETIME COMPARISON BETWEEN PSO-UFC, EBUC, PSO-C, AND LEACH-C PROTOCOLS

Scenario	Protocols	Rounds			
		500	1000	1500	2000
WSN #1	LEACH	200	130	0	0
	PSO-C	200	192	11	0
	EBUC	200	200	54	0
	PSO-UFC	200	200	194	32
WSN #2	LEACH	200	9	0	0
	PSO-C	200	18	0	0
	EBUC	200	200	42	0
	PSO-UFC	200	200	191	28

WSN#2 respectively. Compared with EBUC, PSO-C and LEACH-C protocols, the PSO-UFC protocol maintains less energy consumption in both scenarios. The reason is the proposed protocol elects optimal relay MCH nodes in order to balance the intra-cluster and inter-cluster traffic load among the MCHs.

VI. CONCLUSION

In this paper, a particle swarm optimization based unequal and fault tolerant clustering protocol is proposed to address the hot spot problem, imbalanced clustering, and fault tolerance issues. The aim of PSO-UFC protocol is to elect more number of MCHs in the area closer to the base station to solve the hot spot problem. By utilizing unequal clustering mechanism, the PSO-UFC constructs an optimum number of clusters and multi-hop routing tree between the MCHs in order to balance the intra-cluster and inter-cluster energy consumption. Moreover, the fault tolerance mechanism prevents the MCHs from sudden failure due to their complete energy depletion. The simulation results are compared with the existing related protocols namely, EBUC, PSO-C, and LEACH-C. We have shown that PSO-UFC protocol delivers better performance than its comparatives in terms of network lifetime and total energy consumption. As a future work, we plan to study the design of a TDMA frame in the case of variable traffic load.

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