Uneven clustering and fuzzy logic based energy-efficient wireless sensor networks

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ABSTRACT

Clustering is the fundamental issue in terms of ensuring long-term operation of wireless sensor networks (WSNs). The problem of hot spots remains the most prominent research challenge relating to the design of energy-efficient clustering algorithm. This paper proposed a protocol, namely an uneven clustering and fuzzy logic-based energy-efficient (UCFLEE), for prolonging network lifetime. Depending on the communication distance, the UCFLEE protocol divides the network into uneven clusters for suppressing the hot spot problem. The fuzzy logic selects the optimal cluster head in accordance with certain parameters. The advocated method adopts a dynamic energy threshold to chnage the cluster head. The UCFLEE protocol is dependent on the iterative deepening A (IDA) star algorithm for identifying the routing path from the cluster heads to the base station. The IDA-star method is reliant upon a cost bounded method to select the optimal solution for the base station. The UCFLEE protocol is tested and subsequently contrasted with other protocols. The results obtained from the UCFLEE protocol enable an energy consumption equilibrium, eradicates the hot spot challenge, while also attaining maximum network lifetime.

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1. INTRODUCTION

Wireless sensor networks (WSN) is a significant and evolving form of communications network that may be adopted in order to sense numerous environmental and physical parameters (for example humidity, smoke, pressure and temperature) [1], [2]. A WSN is formed from integrated and miniaturised sensor nodes, embedded systems, wireless communications, in addition to other technologies [3]. WSN nodes have limited energy resource capabilities, whole typically being unreachable and unmanned [4]-[6]. Accordingly, conserving energy and the means of identifying an energy-efficient strategy for extending network lifetime have emerged as fundamental challenges in relation to WSN design.

Clustering is the most prominent issue in terms of accommodating the limited resources of sensor nodes in WSNs, particularly in relation to energy capacity [7], [8]. Clustering aims to diminish the network's energy consumption by gathering those nodes possessing equivalent characteristics, or those nodes in close proximity, to form clusters. The base station (BS) elects the cluster head (CH) per cluster so as to manage the cluster activities. The CHs are responsible for aggregating the sensed data in order to measure physical phenomenon of interest from their member nodes. Subsequently, the CHs forwards the aggregated data directly to the BS or via relay CHs [8], [9].

Numerous clustering protocols have been presented with the aim of lengthening the network lifespan via optimising energy management. Heinzelman *et al*. [10], the authors designed a first clustering protocol, namely low energy adaptive clustering hierarchy (LEACH), which adapted the network to evenly share an energy load among the nodes. The LEACH protocol formed nodal clusters and adopted a local node as a head of members per cluster. The authors proposed a LEACH-C as the protocol, which enhances the performance of the LEACH protocol [11]. This protocol involves the BS selecting various CHs and placing each CH at the centre of a cluster. Liang *et al.* [12], the authors proposed the PSO-C protocol to provide the WSN with a higher lifetime. The proposed scheme applies the PSO algorithm as a means of calculating the optimal CH as well as the fitness function, thus optimising the WSN's energy efficiency and reducing consumption. The aforementioned protocols used the single communication approach between the CHs and the BS. The CHs suffer from preliminary death when they are located at great a distance from the BS [13], [14].

Cengiz and Dag [15] presented a novel protocol called multi-hop low energy fixed clustering algorithm (MLEFCA), as a means of limiting the energy dissipation. The MLEFCA protocol offers a multi-hop routing to the BS via electing the closer neighbour CH as a relay node. Selvi *et al*. [16], the researchers proposed the honey bee optimization (HBO) technique in order to balance energy consumption, through selecting the optimum routing path. The HBO technique utilised the enhanced k-means algorithm to form the clusters, in addition to the HBO algorithm to determine the path to the BS. The balanced residual energy-LEACH (BRE-LEACH) is an original protocol introduced to expand network lifetime [17]. The BRE-LEACH protocol depends on the remaining energy to select the best CH. This proposed approach selects the optimal CH as the root CH. The farthest CHs used the multi-hop path to aggregate data at the root CH. In multi-hop wireless communication, the CHs nearest to the BS aggregate the data packet from the farther CHs. The CHs nearest to the BS are exerting additional energy compared with other CHs, as a result of data dissemination and heavy traffic. This creates a hot spot problem in WSNs and swifter expenditure of energy by the CHs [18]-[21]. Consequently, selecting the CH and resolving the hot spot problem are the foremost challenges to account for while designing energy efficient clustering.

For load balance achievement and mitigation of the hot spot problem, this paper advocates a protocol named uneven clustering and fuzzy logic-based energy-efficient (UCFLEE). Based on the communication distance, the UCFLEE protocol divides the network area into two sectors of different sizes. The smaller sector is situated in closer proximity to the BS, whereas the larger sector is located farther away from the BS. The larger sector is further divided into equal size sectors in accordance with the communication distance. The proposed protocol utilises fuzzy logic as a means of identifying optimal CHs. The CH change is dependent on the energy threshold to equally distribute the CHs' roles between the nodes. The proposed scheme developed the iterative deepening A (IDA) algorithm to establish the multi-hop path to the BS.

The remainder of this paper is as shown in: section 2 describes the system model. The UCFLEE protocol is discussed with all its details in section 3, while section 4 details the UCFLEE protocol's overall performance following the completion of the simulation trials. In section 6, the conclusions obtained from this paper are presented.

2. SYSTEM MODEL

2.1. Network model

The network comprises of numerous sensors that are disseminated randomly throughout the network. The following properties describe the network sensors: i) The BS is immobile and aware of the nodes locations; ii) The BS used a sufficient amount of resources to manage the network; iii) Nodes are static, with each sensor having a unique identification while also being unaware of the location; and iv) Initially, nodes have the same amount of appropriated energy, computation capabilities and communication power.

2.2. Energy model

The node battery is consumed significantly via the data communication process (data transmission and data reception). The first radio model is used to compute the energy consumed by the nodes [11]. The energy consumed to transmit (E_{c-tx}) and receive (E_{c-Rx}) n-bit data over communication distance d metres may be calculated by (1)-(3):

$$E_{c-tx}(n,d) = \begin{cases} n \times E_{elec} + n \times \in_{fs} \times d^2 & d \leq d_{Threshold} \\ n \times E_{elec} + n \times \in_{mp} \times d^2 & d > d_{Threshold} \end{cases} \quad (1)$$

$$E_{c-Rx}(n,d) = n \times E_{eleec} \quad (2)$$

$$E_{c-total} = E_{c-tx}(n,d) + E_{c-Rx}(n,d) \quad (3)$$

E_{elec} indicates the electronic circuit's energy consumption, while either $\in_{fs}$ (free space channel)or $\in_{mp}$ $(multipath\ fading)$ denote the transmitter amplifier's energy consumption. Either $\in_{fs}$ or $\in_{mp}$ are used depending on the communication distance (d) between the nodes. $d_{Threshold}$ refers to the threshold distance, which may be determined in (4):

$$d_{Threshold} = \frac{\in_{fs}}{\in_{mp}} \quad (4)$$

3. PROPOSED UCFLEE PROTOCOL

3.1. Sector formation phase

The BS partitions the network area into two sectors of varying size. The smaller sector is situated nearer to the BS, whereas the larger sector is located at some distance from the BS. According to (5), the BS determined the smaller sector's size, where R denotes the maximum range of communication distance. The clusters' small size averts the premature death of those nodes in closer proximity to the BS, therefore resolving the hot spots issue. The larger sector is that beyond the smaller sector. The BS divided the larger sector into sub-sectors, with each sub-sector's size being equal to R. In the network area, each sector is partitioned into clusters of equal width. Each cluster's width is always equal to the value of $\text{sector}_{smaller}$ in (5). Figure 1. presents the sector formation phase. Algorithm 1 clarifies all of the steps involved in the sectors' formation.

$$\text{sector}_{smaller} = \frac{R}{2} \quad (5)$$

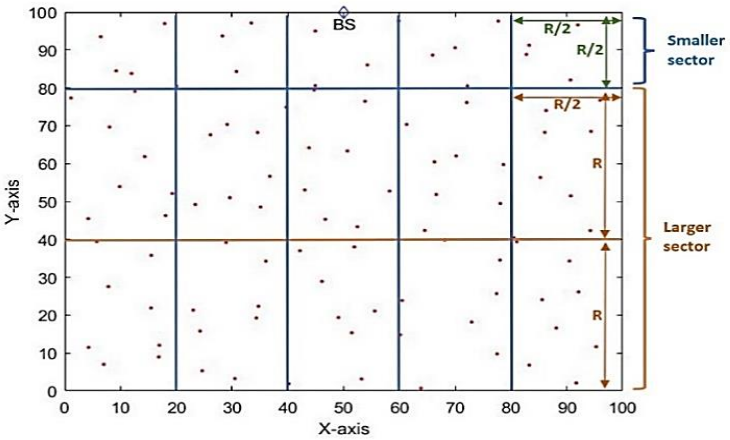

Figure 1. Sector formation phase

Algorithm 1. Sector formation phase

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Input: Network region dimension (X*Y;
Output: Forming sectors.
Initial x_axis = 0, y_axis = 100, i = 1, R
 While ( y_axis > 0)
 If ( y_axis = 100)
 y_axis-new = y_axis - R/2
 Else
 y_axis-new = y_axis - R
 EndIF
 y_axis = y_axis-new
 While (x_axis < X)
 x_axis-new = x_axis + R/2
 Cluster_id = i
 i = i +1
 End while
 x_axis = 0
End while
```

3.2. CH selection phase

The BS utilises the fuzzy logic (FL) model in order to select the optimal CH per cluster. Two input variables, namely the distance to BS as well as residual energy, are given to the FL model, while the output variable is produced, namely CH chance. Table 1 presents the tabulation of the membership functions for the input and output variables. The value range of the distance to BS as well as residual energy parameters are [0-120] and [0-0.5] respectively, as presented in Figures 2 and 3. The output variable's value range is [0-1], as evidenced in Figure 4.

In the FL model, every input variable's value is transformed into the linguistic variable via the fuzzification process. Subsequently, if-then rules may be applied in relation to the linguistic variables as a means of connecting the input parameters and relevant output variables. A total of 25 (5^2) if-then rules are performed depending on two input variables, as Table 2 clarifies. Lastly, by applying the centre of area method, the defuzzification process enables the output linguistic variables to be transformed into the output value [22].

The BS uses the dynamic energy threshold (DT) to chnage the CH in each cluster. According to (6), the BS calculates the DT value at the conclusion of each round. The CH changes whether its residual energy was below the DT value. Algorithm 2 describes the CH selection method.

$$\mathrm{DT} = \frac{1}{N} * \ E_{total} * \left(1 - \frac{r_{\text{current}}}{R_{\text{estimated}}}\right) \tag{6}$$

E_{total} indicates the total energy during the network's initial operation. The r_{current} pertains to the numeral of the current round, while $R_{\text{estimated}}$ refers to the number of estimated rounds until expiry of all of the network's nodes. N denotes the total sensor number. As shown in (7) represents the $R_{\text{estimated}}$ value, when $E_{Current}$ is the current round's energy consumption:

$$R_{\text{estimated}} \ = \frac{E_{total}}{E_{current}} \tag{7}$$

Table 1. Membership function for the proposed protocol

Variable	Membership function
Distance to BS	Very Close (D_{VC}), Close (D_C), Medium (D_M), Far (D_F)Very Far (D_{VF})
Residual Energy	Very High (RE_{VH}), High (RE_H), Medium (RE_M), Low (RE_L), Very Low (RE_{VL})
CH Chance	Very Strong (C_{VS}), Strong (C_S),Medium (C_M), Weak (C_W), Very Weak (C_{VW})

Table 2. Fuzzy rules for the proposed protocol

No.	Residual Energy	Distance to BS	Chance
1	RE_{VL}	D_{VF}	C_{VW}
2	RE_{VL}	D_F	C_{VW}
3	RE_{VL}	D_M	C_{VW}
4	RE_{VL}	D_C	C_{VW}
5	RE_{VL}	D_{VC}	C_W
6	RE_L	D_{VF}	C_{VW}
7	RE_L	D_F	C_W
8	RE_L	D_M	C_W
9	RE_L	D_C	C_M
10	RE_L	D_{VC}	C_M
11	RE_M	D_{VF}	C_W
12	RE_M	D_F	C_W
13	RE_M	D_M	C_M
14	RE_M	D_C	C_M
15	RE_M	D_{VC}	C_S
16	RE_H	D_{VF}	C_M
17	RE_H	D_F	C_M
18	RE_H	D_M	C_S
19	RE_H	D_C	C_S
20	RE_H	D_{VC}	C_{VS}
21	RE_{VH}	D_{VF}	C_S
22	RE_{VH}	D_F	C_S
23	RE_{VH}	D_M	C_{VS}
24	RE_{VH}	D_C	C_{VS}
25	RE_{VH}	D_{VC}	C_{VS}

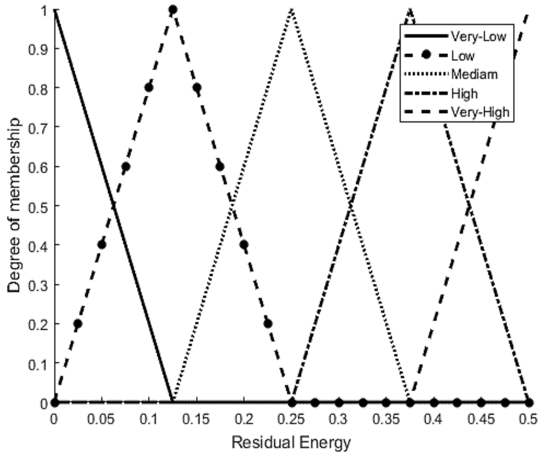

Figure 2. The member function for distance to BS

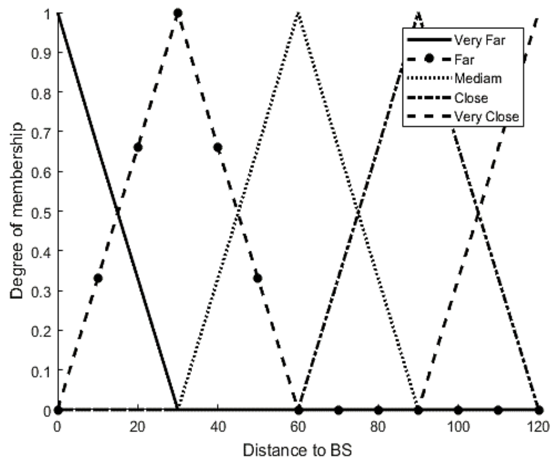

Figure 3. The member function for residual energy

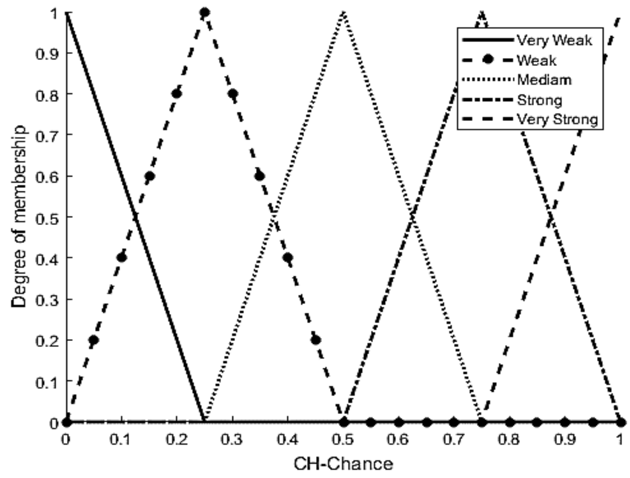

Figure 4. The member function for the output variable

Algorithm 2. CH selection method

Input: $E_{current}$, E_{total} , $r_{current}$, $Cluster_{id}$, N
Output: CH selection in each round

$R_{estimated=}\frac{E_{total}}{E_{current}}$

$$DT = \frac{1}{N} * E_{total} * (1 - \frac{r_{current}}{R_{estemated}})$$

IF ($r_{curretn}$ = 1)
 For each $Cluster_{id}$ **do**
 For each node in Cluster **do**
 - Calculate Fuzzy Value for each node
 End For
 -Select node to be CH that have best Fuzzy Value
 End For
Else
 For each Clusterid **do**
 IF (CH_{energy} < DT)
 For each node in Cluster **do**
 - Calculate Fuzzy Value for each node
 End For
 -Select node to be CH that have best Fuzzy Value
 End IF
 End For
End IF

3.3. Data routing phase

The BS adopts the iterative deepening A* (IDA-star) method to discover the optimal multi-hop path from the CHs. The IDA-star method enables the establishment of the shortest path with the least memory usage based on iterative deepening [23]-[25]. Furthermore, the IDA-star algorithm determines the evolution function of cluster heads $f(CH_s)$ in accordance with (8). The IDA-star algorithm is reliant upon two parameters to calculate the f value, namely energy level (E_{CH}) and the distance to the BS (d_{CH-BS}). The IDA-star algorithm uses the cost bounded ($\text{Cost}_{\text{bounded}}$) value to determine the optimal solution to the BS, which is expressed by (9).

$$f(CH_s) = d_{CH-BS} + E_{CH} \quad (8)$$

$$\text{Cost}_{\text{bounded}} = \text{smallest}\ (\ f(CH)\ ) \quad (9)$$

The value of $\text{Cost}_{\text{bounded}}$ is the f value of the CH for the initial state. Per new level, the $\text{Cost}_{\text{bounded}}$ is the smallest f value among all the CHs that exceeded the previous $\text{Cost}_{\text{bounded}}$ of the preceding level. The CH collects data from the sensor nodes. Subsequently, the CH with an f value that exceeded the cost bounded is added to the list called the ‘previous list’. In this previous list, the CH with a larger f-value is added to the optimal path list, enabling its selection as the next hop. The IDA star continues until the optimal path has been guaranteed based on attaining the BS.

Having completed the routing path, the CH that has the information sends the route request (RREQ) message to the next CH in the optimal path. The CH waits for the route reply (RREP) message. Having delivered the RREP message, the information is sent to the next CH. This process repeats from the next CH in the routing path, until the information has been delivered to the BS. Following each round, the BS checks the possibility of the current path sending further information or not, by comparing the energy per CH that exists in this path with the DT value. If the DT value exceeds the energy of CH, then the BS adopts the FL model to identify the new CH in the cluster.

4. PERFORMANCE EVALUATION

The UCFLEE protocol’s performance is evaluated by conducting simulation experiments. The simulation was undertaken utilising the MATLAB environment. 100 nodes were spread to the sensing region $100\ m * 100\ m$. The precise BS position was $100\ m *\ 50\ m$ of the network area. Table 3 presents further details of all the adopted simulation parameters. The proposed UCFLEE is compared with two widely recognised clustering protocols, namely BRE-LEACH [17] and PSO-C [12]. All protocols’ performance analyses are informed by the evaluation variables, for example network lifetime and total residual energy per round. The performance of the UCFLEE protocol, BRE-LEACH and PSO-C may be described as follows, depending on the above factors.

Table 3. The simulation parameters of WSNs

Parameter	Value
Area	$100\ m * 100\ m$
N	100 nodes
$\boldsymbol{R}$	$40\ m$
Position of BS	$100\ m *\ 50\ m$
Initial amount of energy	0.5 J
Data Packet	4000 bit
ϵ_{mp}	0.13 bit/m^4
$\boldsymbol{E_{elec}}$	50 nJ/bit
ϵ_{fs}	10 pJ/bit/m^2

4.1. Network lifetime

The time interval between beginning the network operation to the death of the last node is represented as the network lifetime [26]. Figure 5 presents the network lifetime performance for the UCFLEE protocol as well as other protocols. This figure evidences that for BRE-LEACH and PSO-C, every node had died by 5000 and 6739 rounds respectively. Contrastingly, for the UCFLEE protocol, only 53 nodes died at 9000 rounds. Therefore, the UCFLEE approach contributes to lengthening the network lifetime to a greater extent than the BRE-LEACH and PSO-C protocols, by 64% and 56% respectively. The DT concept to alter the CHs and the FL model in order to select the optimal CHs is the principal reason for the UCFLEE protocol being more effective than other related protocols with regard to the network lifetime.

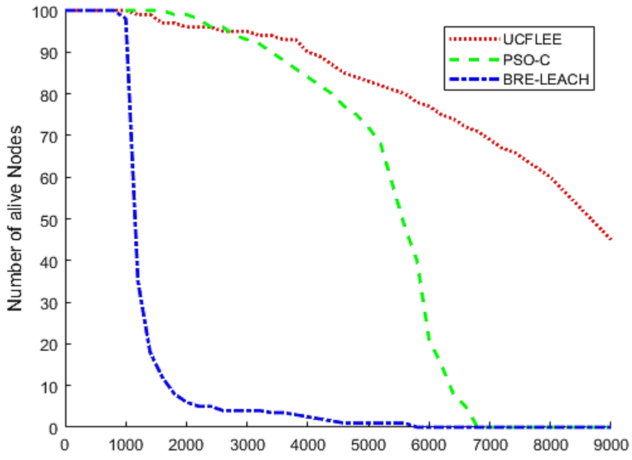

Figure 5. The network life time performance

4.2. Residual energy

Figure 6 presents the results of the total residual energy for the three approaches. After 7000 rounds, the energy in BRE-LEACH and PSO-C is completely consumed, whereas the proposed protocol preserves over 23% of its energy at 7000 rounds. With the UCFLEE strategy, the nodes' energy is depleted more slowly compared with other protocols, meaning that it enables effective conservation of the nodes' remaining energy. The DT contributes to continuing the CH for multiple rounds without change and distributing the traffic load between the nodes, thus saving greater energy. Moreover, the $\mathrm{Cost}_{\mathrm{bounded}}$ in IDA-star facilitated the diminishing of the nodes' traffic load by expanding only those CHs with high f- value. Evidently, the proposed UCFLEE protocol can achieve effective equilibrium of energy consumption, keeping the majority of nodes alive to a greater extent than the related protocol.

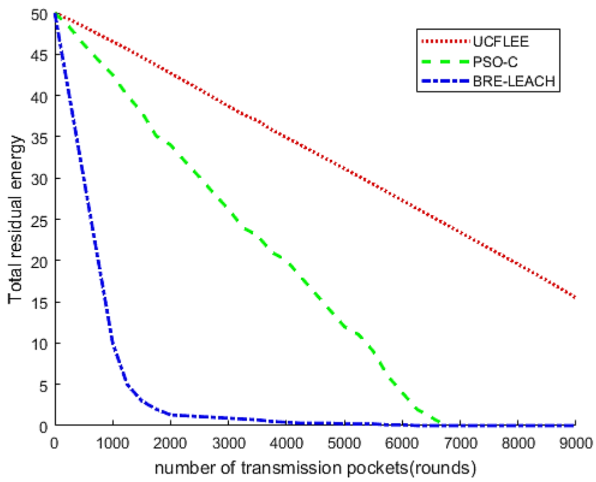

Figure 6. The total residual energy for for all of the protocols the three protocols

5. CONCLUSION

A new protocol for WSNs called UCFLEE has been presented in this paper. The UCFLEE protocol considers the issues of minimising energy dissipation and load balancing. The UCFLEE protocol contributed to minimising the hot spot problems and facilitated the identification of efficient routing to the base station. The concepts of altering and selecting cluster heads are employed to decrease energy dissipation and to balance the nodal loads. The threshold concept is engaged to enable all nodes to consume an equivalent amount of energy. The extensive experimentations confirm that the UCFLEE scheme significantly decreases the node's energy consumption, while enhancing network lifetime to a greater extent than the previous protocols.

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