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Energy-Balanced Unequal Layering Clustering in Underwater Acoustic Sensor Networks

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ABSTRACT Underwater acoustic sensor networks (UASNs) are used extensively in activities such as underwater data collection and water pollution detection. An UASN consists of acoustic sensors that use batteries as their power supply. Because of the complex underwater environments in which UASNs are employed, replacing these batteries is difficult. Prolonging the battery life of UASNs by reducing their energy consumption (improving their energy efficiency) is one of the means of mitigating this problem. This paper proposes an energy-balanced unequal layering clustering (EULC) algorithm that improves the energy efficiency of acoustic sensors. The EULC algorithm designs UASNs with unequal layering based on node depth, providing a solution to the ''hot spot'' issue through the construction of clusters of varying sizes within the same layer. Simulation results show that the EULC algorithm effectively balances the energy in UASN nodes and thereby prolongs network lifetime.

INDEX TERMS Underwater acoustic sensor networks, unequal layering, clustering, energy-balance.

I. INTRODUCTION

Underwater acoustic sensor networks (UASNs) are widely used in activities such as sea information collection and underwater resource exploration. Having attracted substantial attention from researchers, they are now a topic of significant interest in the sensor network technology field [1]–[3]. A UASN comprises a limited number of acoustic sensor nodes located within a complex underwater environment, which makes node battery recharge very difficult [4]. Thus, reducing UASN energy consumption, prolonging network lifetime, and promoting energy consumption efficiency have become key issues in the UASN research field.

Optimal routing protocols, such as clustering routing by dividing sensor nodes into several clusters for distributed management, can effectively promote UASN energy consumption efficiency [5]. In recent years, clustering routing has been widely applied in the wireless sensor networks (WSNs) used for energy-related research. Heinzelman *et al.* [6] proposed a clustering algorithm, called low energy adaptive clustering hierarchy (LEACH), in which all nodes take turns at playing the role of cluster-head to reduce energy consumption. However, the process for cluster-head selection is randomized and can result in variable numbers of cluster-heads. Younis and Fahmy [7] improved on the limitations of LEACH in proposing the hybrid energy-efficient distributed (HEED) clustering approach. HEED considers clustering-head candidate density and residual energy, and enables more integration among nodes in a single cluster. LEACH and HEED are two typical equal-clustering approaches used in WSNs.

To make clustering more flexible, several unequal-clustering approaches have been proposed. Li *et al.* [8] proposed an energy-efficient unequal clustering (EEUC) algorithm that addresses the issue of unbalanced cluster-head energy consumption by shrinking the size of the clusters close to the sink. Selvi and Manoharan [9] proposed an unequal clustering algorithm (UCAPN) for WSNs that prolongs network lifetimes. Under UCAPN, sensor nodes are divided into clusters of different sizes and non-cluster-head node information is first directly transmitted to the nearest cluster-head and then transmitted to the sink node to balance node energy consumption and prolong network lifetime.

To facilitate better understanding of the effect of energy and water depth on clustering performance, Cao *et al.* [10] analyzed the relationship between the receiving and transmitting energy consumption of UASNs and proposed an energy-level-based hybrid transmission (ELT) approach to balance energy consumption, and thereby prolong network lifetime. Liaqat *et al.* [11] proposed the depth-based energy-balanced hybrid (DB-EBH) algorithm, in which sensor nodes are deployed in a linearly random manner. Through the application of a hybrid direct/multi-hop hybrid communication method and prior forwarding based on node depth, DB-EBH balances energy consumption and prolongs network lifetime. Kannan *et al.* [12] proposed a distributed cluster-head scheduling (DCHS) algorithm in which networks are divided into primary and secondary layers and cluster-heads are selected based on the receiving signal power and residual node energy to avoid frequent cluster-head selection and prolong network lifetime.

In an attempt to encourage the development of routing systems that can increase WSN lifetime, network structure based clustering approaches have been proposed. Das and Astya [13] performed a deep analysis of LEACH and discussed the advantages and disadvantages of its respective routing protocols. Wang *et al.* [14] proposed an energy-efficient data UASN transmission scheme called energy-efficiency grid routing based on 3D cubes (EGRCs) that considers the complex properties of the underwater medium such as changing 3D topologies, high propagation delays, node mobility, and density, and the rotation mechanisms of cluster-head nodes. In an attempt to reduce the energy consumption of cluster head nodes, reduce propagation delay, and prolong network life cycles, Aslam *et al.* [15] proposed the energy-efficient logical cubical layered path planning algorithm (EECPPA) and multiple sink EECPPA (MSEECPPA) for 3D UASNs.

Focusing on the attributes of sensor nodes, Li *et al.* [16] proposed a new clustering model that considers the required transmission power of sensor nodes, cluster head residual energy, and cluster head loads to improve upon the poor stability and unsatisfactory clustering results of existing UASN clustering algorithms.

Although the above approaches can optimize energy consumption, virtually all are applicable only to WSNs. UASNs differ significantly from conventional WSNs in terms of factors such as usage environment and data communication method. For UASNs, Zhang *et al.* [17] proposed a depth- and energy-based clustered routing (DEBCR) algorithm for use in three-dimensional underwater environments, in which the selection of cluster-heads is based on depth and residual energy, with non-cluster-head nodes selecting their clusters based on the differences between their depths and those of the respective cluster-head nodes, resulting in a conical network structure. However, the DEBCR algorithm cannot guarantee the quantity stability of cluster-heads.

Considering the limitations of the approaches cited above, an energy-balanced unequal layering clustering (EULC) algorithm is proposed in this paper. The proposed EULC algorithm differs from the above approaches in three main respects. First, it divides the UASN into layers based on the depth and clusters within each layer. The algorithm's selection of cluster-heads takes each node's residual energy, node degree, and distance to the sink node into account, resulting in a more uniform distribution of cluster-heads. Second, it sets the contending radii for each cluster-head according to the distance between the cluster-head and the sink node, which reduces the cluster scale closer to the sink node, thus prolonging node lifetime and addressing the "hot spot" issue. Third, it uses single- and multi-hop routing for, respectively, intra- and inter-cluster data transmission. To reduce energy consumption in inter-cluster communication, the next-hop node is selected in accordance with its residual energy and depth.

The remainder of this paper is organized as follows. Section II describes the underwater communication system model. Section III presents the proposed EULC algorithm, in which issues concerning unequal layering modeling, cluster-head election, cluster establishment, and the data transmission stage are also discussed. A comprehensive simulation that was conducted to verify the efficiency of EULC is outlined in Section IV. Finally, Section V presents concluding remarks.

II. SYSTEM MODEL

Fig. 1 shows the three-dimensional UASN structure, which comprises static sensor nodes affixed to the seabed, dynamic sensor nodes floating in the water, and a sink node floating on the surface of the water. During the UASN deployment phase, sensor nodes are randomly distributed within a cubic volume and the sink node is placed on the water surface. This model assumes the following:

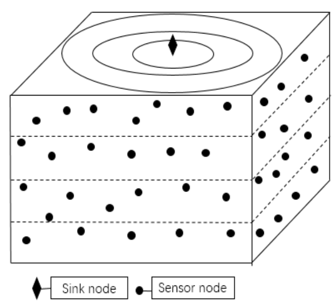

FIGURE 1. Three-dimensional UASN structure.

1) All sensor nodes are deployed within a cubic volume of water and share common structures and energies, but have unique IDs; additionally, each node knows its location.
2) Each node can assume the role of either a normal or a cluster-head node. All nodes have the ability to integrate data packets and adjust transmitting power based on data transmission distance.

3) The sink node is located at the center of the three-dimensional network's top surface and can communicate with all nodes in the network.
4) The sensor nodes periodically collect data. Nodes in a given layer transmit data to the cluster-head of that layer, which in turn sends data to the cluster-head one layer up, with the cluster-head at the top layer sending data to the sink node.

Based on the energy consumption model of underwater acoustic communication proposed by Sozer *et al.* [18], we let P_0 denote the data-receiving power per node, $A(d)$ the power attenuation coefficient as a function of distance, d, and T_l the time delay in sending l bits of data via a data-sending node. Then, the energy consumption of sending l bits of data can be written as

$$E_{send}(l, d) = T_l \cdot P_0 \cdot A(d), \tag{1}$$

with $A(d)$ represented as

$$A(d) = d^{\mu} \cdot c^{d}, \tag{2}$$

where μ is an energy factor reflecting the type of acoustic communication used in the model, with $\mu = 1$ and $\mu = 2$ denoting cylindrical and spherical propagation models, respectively. In addition, c is the power attenuation coefficient, which can be written as

$$c = 10^{\partial(f)/10}, \tag{3}$$

where $\partial(f)$ is the energy absorption coefficient, which can be written as

$$\partial(f) = 0.11 \times \frac{f^2}{1+f^2} + 44 \times \frac{f^2}{4100+f^2} + 2.75 \times 10^{-4} \times f^2 + 0.003 \tag{4}$$

The energy consumed per sensor node in receiving l bits of data can be written as

$$E_{receive}(l) = l \cdot E_{process}, \tag{5}$$

where $E_{process}$ is the energy consumption of one acoustic sensor node in processing one bit of data. In UASNs, the data-receiving energy consumption is relatively small compared to the total energy consumption of data transmission.

The energy consumption of an acoustic sensor in integrating l bits of data can be written as

$$E_{Integrate}(l) = l \cdot E_1, \tag{6}$$

where E_1 is the energy consumed to integrate one bit of data.

III. EULC ROUTING ALGORITHM

A. UNEQUAL LAYERING MODEL

Layering can enable uniform distribution of cluster heads in UASNs, simplifying the network model and helping balance its energy consumption. To address the "hot spot" issue, the EULC model divides UASNs into layers with an unequal layer spacing that gradually increases from top to bottom. The acoustic sensor nodes cluster exclusively within their layers with contending radii set based on the distances between the respective cluster-heads and the sink node.

Letting h_i be the underwater depth of an acoustic sensor node, i, a UASN can be divided into s layers according to the nodes' depths, with the spacing in the k^{th} layer denoted as $r_k (k = 1, 2, \ldots, s)$, which satisfies $r_k = r_{k-1} + \Delta r$ (where Δr is a constant). An acoustic sensor node satisfying $h_i < r_1$, where r_1 equals the original communication radius, R_0, will be located in the first layer. In the UASN, node i can calculate its specific layer using

$$L_i = \left\lceil \frac{h_i + \Delta r}{R_0 + \Delta r} \right\rceil \tag{7}$$

B. CLUSTER-HEAD ELECTION

Cluster-heads play a key function in UASNs. In EULC, the cluster-heads are set dynamically. At the start of UASN deployment, the sink node broadcasts information to all nodes in the network; each node calculates its distance to the sink node based on the received signal power and then estimates its layer based on its depth. After layering, all nodes enter the cluster-head election stage. In EULC, cluster-heads are dynamically selected by turns, each involving cluster-head election, cluster establishment, and data transmission stages. Within each layer, the node selected as the cluster-head must make note of its residual energy, node degree, and distance to the sink node.

The node degree of node i at the k^{th} layer is defined as

$$N_{k\_i} = M_{k\_i}/N_k, \tag{8}$$

where M_{k_i} is the adjacent node set of nodes i at the k^{th} layer, which can be denoted as $M_{k\_i} = \{j|$ node i, j at the same layer, and $d_{i-j} \leq R_{i,comp}$, where $R_{i,comp}$ is the contending radius of node i, as defined in (9)$\}$, d_{i-j} is the distance between nodes i and j, and N_k is the total number of nodes in the k^{th} layer. The contending radius of node i is given by

$$R_{i,comp} = (1 - c \cdot \frac{d_{\max} - d_{i-Sink}}{d_{\max} - d_{\min}}) \times R_c, \tag{9}$$

where $d_{\max}$ and $d_{\min}$ denote, respectively, the longest and shortest distances for all nodes, d_{i-Sink} is the distance from node i to the sink node, $c (0 \leq c \leq 1)$ is an adjustment factor, and R_c denotes the average spacing between all layers.

The cluster-head election weight for node i at the k^{th} layer is defines as

$$W_{k\_i} = \begin{cases} \alpha \cdot \frac{E_{res}(k\_i)}{E_{ini}(i)} + \beta \cdot \left(1 - \frac{d_{i-Sink}}{d_{\max}}\right) + \gamma \cdot N_{k\_i}, & E_{res}(k\_i) > E_{res}(k) \\ 0, & E_{res}(k\_i) \leq E_{res}(k) \end{cases} \tag{10}$$

where $E_{res}(k\_i)$ is the residual energy of node i, which is determined by its original energy $E_{ini}(i)$ and the data processing energy consumption, and α, β, and γ are adjustment factors to the original energy, distance to the sink node, and node degree, respectively, for node i, which satisfy $0 \leq \alpha, \beta, \gamma \leq 1$

and $\alpha + \beta + \gamma = 1$. $E_{res}(k)$ denotes the average residual energy for all nodes at the k^{th} layer. When the residual energy of node i is less than $E_{res}(k)$, it ceases cluster-head election.

As the UASN nodes are randomly distributed, energy can be saved by not requiring that all nodes join in the cluster-head elections. To enable this, at each turn each node generates an election threshold $T(k\_i)$ to determine whether to join in the election, which can be defined as follows:

$$T(k\_i) = 0.9^{L_i} \times P_c \times W_{k\_i}, \quad (11)$$

where P_c denotes the occupation ratio of the original number of cluster-heads to the total number of nodes.

C. CLUSTER ESTABLISHMENT

Cluster establishment takes place in two stages: cluster-head election and cluster establishment. This process is described as follows.

In the first step, in accordance with their respective election thresholds and conditions the nodes in a given layer become cluster-head candidates, broadcasting cluster-head compete messages including cluster-head IDs, compete radii, weights, etc. The node with the largest weight is then elected as the cluster-head and broadcasts a message within its compete radius to announce its election.

In the second step, upon receiving the successful cluster-head's election message the other cluster-head candidates within the layer withdraw from the election and join in the cluster, along with the non-cluster nodes within the layer.

D. DATA TRANSMISSION STAGE

Within each cluster, non-cluster-head nodes send packets to the cluster-head node, which then integrates the packets and exports the result to the next cluster-head, which in turn further integrates and exports upwards. In EULC, each cluster-head hold an information table of adjacent cluster-head, as shown in Table 1.

If the adjacent located layer of cluster-head j satisfies $L_j < L_i$, the source cluster-head i saves j's information in its table. Based on the distance between nodes and residual energy, the routing selected function can be given as

$$P(i,j) = \varepsilon \cdot \frac{E_{ini}(j)}{E_{res}(j)} + (1-\varepsilon) \cdot \frac{d_{i-j}^2 + d_{j-Sink}^2}{d_{i-Sink}^2}. \quad (12)$$

TABLE 1. Information table of adjacent cluster-head *j*.

Parameter	mean
ID	Identification
$E_{res}(k\_j)$	Residual energy
d_{j-Sink}	Distance to sink node
d_{i_j}	Distance to node i
L_j	Located layer

The parameter ε ($\in [0, 1]$) is used to balance the ratio of energy and distance. Source cluster-head i selects the next-hop node with the smallest value of $P(i,j)$.

IV. SIMULATION

To verify the efficiency of EULC, we compared its performance to that of the LEACH and DEBCR algorithms using the MATLAB simulation tool with the parameters listed in Table 2.

TABLE 2. Simulation parameters.

Network size	500 m × 500 m × 500 m
Sink node location (X, Y, Z)	(250,250,0)
Node number	500
Average size of packets	4,000 bits
P_0	3 mW
Size of broadcast packet	200 bits
Frequency f	10 kHz
E_1	5 nJ
$E_{process}$	50 nJ
E_{ini}	2 J
R_0	60 m

The change in the number of cluster-heads can serve as a measure of the stability of a clustering algorithm. Figure 2 shows the evolution of the cluster-head distribution for each algorithm over twenty turns. It is seen that the

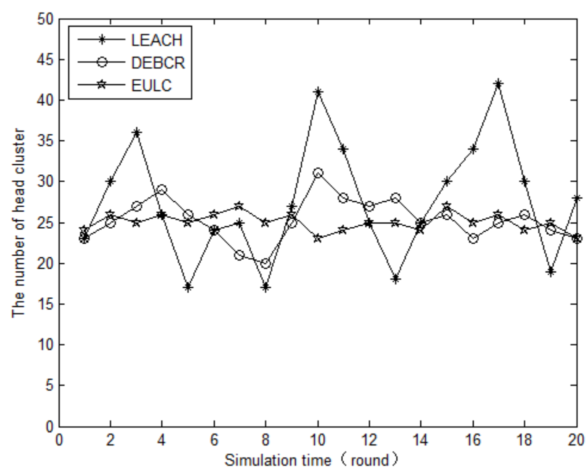

FIGURE 2. Number of cluster-heads in UASN.

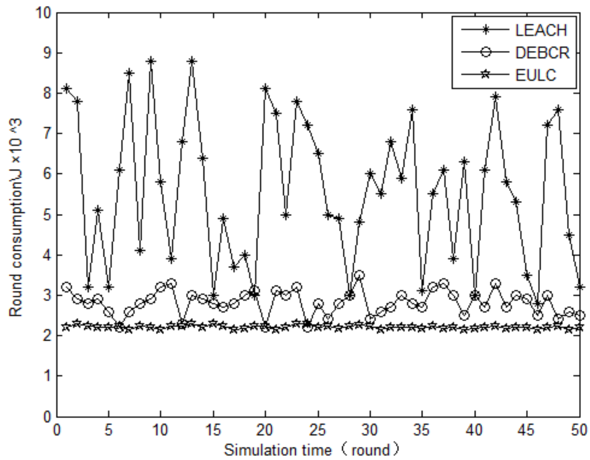

FIGURE 3. Average energy consumption per node over one turn.

numbers of cluster-heads in EULC and DEBCR are more stable than under LEACH; this occurs because LEACH depends on probability measures that are not fixed in each turn to decide the number of cluster-heads per turn, whereas both EULC and DEBCR consider other node attributes in cluster-head election. In particular, EULC's use of an unequal layering approach enforces a more stable number of cluster-heads.

Figure 3 shows the average energy consumption per node over one turn. It can be seen that LEACH has the highest energy consumption and a high degree of jitter, whereas EULC has the lowest energy consumption and the smallest fluctuation range, indicating the high energy efficiency of the EULC algorithm.

Figure 4 shows the evolution of the average residual energies as the number of simulation turns increases. It is clear that LEACH has the highest rate of decrease in average residual energy, which reaches zero at the 325th turn. By contrast, the use by EULC of unequal layering and clustering approaches effectively addresses the "hot spot" issue and

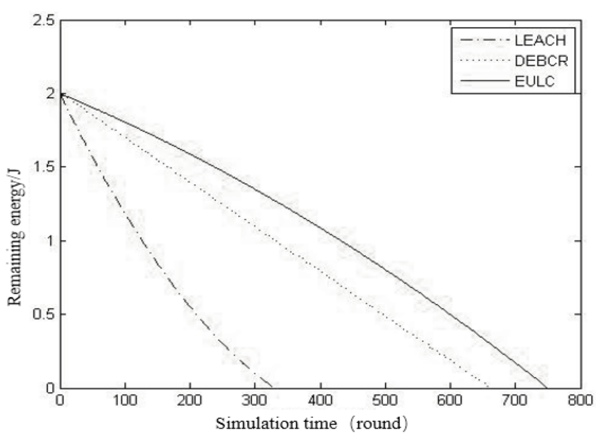

FIGURE 4. Average node residual energy.

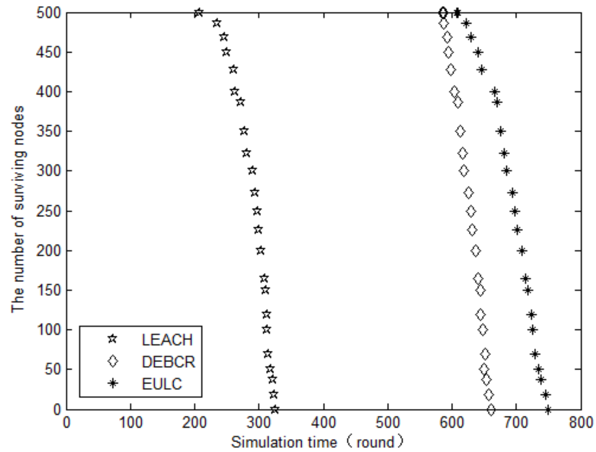

FIGURE 5. Number of surviving nodes.

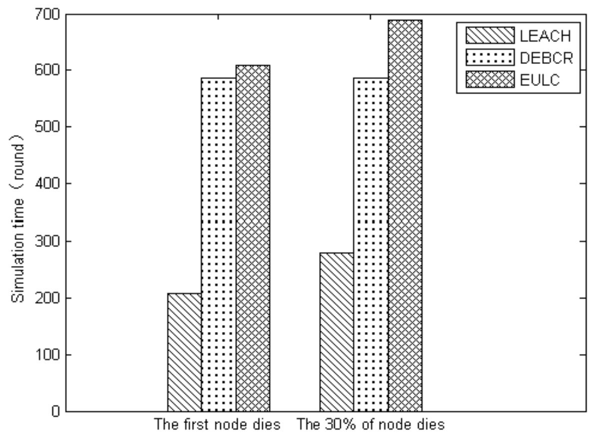

FIGURE 6. Times at which the first node and 30% of nodes die.

balances the inter- and intra-cluster data transmission energy consumption.

Figures 5 and 6 show the nodes' survival periods for the respective algorithms, with Fig. 5 showing the decrease in the number of surviving nodes as the number of turns increase and Fig.6 showing the times at which the first node and 30% of all nodes die. For LEACH, DEBCR, and EULC, the first node dies at the 208th, 587th, and 609th turn, respectively. In LEACH, energy consumption is increased because distant cluster-heads communicate directly with the sink node. Under DEBCR, the selection of cluster-heads takes the nodes' residual energies and node degrees into account, resulting in a more uniform distribution of nodes. In EULC the selection of cluster-heads takes node energy, node degree, and distance to the sink node all into account, making the distribution of cluster-heads even more uniform and the energy consumption more balanced.

Figure 7 shows the number of packets received by the sink node under each algorithm. It is seen that, for a given time period, more packets are received by the sink nodes

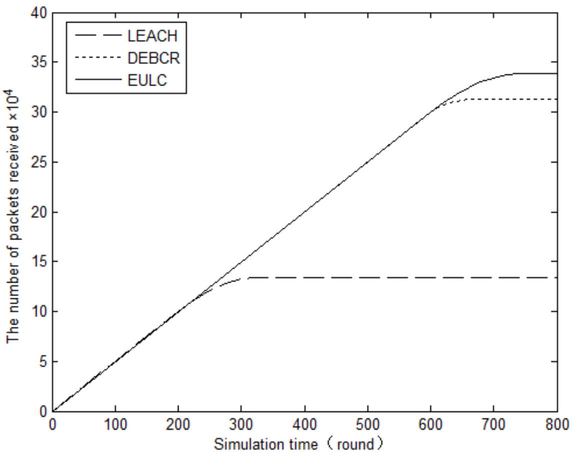

FIGURE 7. Number of packets received by the sink node.

under EULC and DEBCR than under the LEACH algorithm. Of the three algorithms, EULC successfully receives the most packets from cluster-heads, indicating the ability of EULC to efficiently promote network energy utilization.

V. CONCLUSION

Energy efficiency directly affects the lifetimes of UASNs. This paper proposed an energy-balanced unequal layering clustering (EULC) routing algorithm for UASNs. The main advantages of EULC are (1) unequal layering based on sensor node depth; (2) consideration of node residual energy, distance to sink node, and node degree in the election of cluster-heads; (3) ability to addresses the "hot spot" issue by forming clusters at different scales based on distances to the sink node; and (4) determination of the optimal next-hop based on the nodes' residual energies and distances. Simulation results revealed that EULC outperforms the standard DEBCR and LEACH algorithms in terms of energy consumption, cluster-head numbers management, and network lifetime, thus verifying the energy efficiency of using EULC in UASNs.

Several issues remain open for future work, including how to intensively optimize network topology to improve energy efficiency, how to develop differentiated services to support quality-of-service in UASNs, and how to ensure security of data transmission.

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