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A Clustering Algorithm of Underwater Acoustic Sensor Networks based on Hierarchical 3D Mesh

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Underwater acoustic sensor networks (UASNs) are important technical means to explore the ocean realm. As a strategic measure, clustering techniques balance the network energy and survival time obviously. This paper proposes a clustering algorithm for UASNs. First, an UASN structure of hierarchical 3D mesh is defined, and an energy consumption model is built. Second, the algorithm based on the designed framework is presented, including the basic clustering messages, the setup phase and the data transmission phase. Finally, experiment of the algorithm based on WOSS and MATLAB is implemented, and compared with DS-VBF, IAR, and GEDAR in terms of the average end-to-end delay, the survival rate, the number of survival nodes, the number of clusters, and the coverage ratio. Results demonstrate that a tradeoff between clustering performance and network survival is achieved and the algorithm is suitable for UASNs.

Keywords: underwater acoustic sensor networks (UASNs), layered 3D mesh, clustering algorithm, time to live (TTL), DS-VBF, IAR, GEDAR

1. INTRODUCTION

Recently, Underwater Acoustic Sensor Networks (UASNs) have emerged as the key enabler of a wide range of applications [1] in oceans, such as marine data acquisition, environmental monitoring, subaquatic resource survey, earthquake and tsunami monitoring, auxiliary navigation, submarine robots, *etc*. UASNs are composed of a series of sensor nodes, which sprinkle into oceans randomly. Usually, the topologies are variable, and the acoustic is employed for communication and networking. In UASNs, nodes are deployed in redundant manners, and the bandwidth is 10 kHz-40 kHz [2] in common. Compared to traditional underwater systems, UASNs have the advantages of simple infrastructure, small size, low cost, *etc*. However, there are some challenges [3], including high path loss, severe multipath effects, Doppler diffusion, limited bandwidth, and fast channel varying [4].

In an UASN, if each node communicates and transmits data simultaneously, serious congestion and collisions occur. It will lead to the rapid depletion of energy. To improve energy efficiency and reduce the transmission delay, clustering-based routing technologies have been widely concerned [4]. Related algorithms designed to implement routing are built based on clustering. In a clustering algorithm, multiple adjacent nodes form a

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cluster. In a cluster, a CH (Cluster Head) is elected, while other nodes are set to CMs (Cluster Members). A CH is in charge of collecting data from CMs in a cluster and transmitting the aggregated data to the specified BS (base station) or the surface sink node. In these algorithms, a CH provides scalability for a large number of nodes and reduces the energy consumption [5]. Traditional clustering algorithms usually select the nodes with the largest residual energy as CHs, and may consider the distance from them to BS or the sink node. To achieve energy balancing and prolong the network lifetime, CHs are elected based on polling techniques periodically. However, preference of CHs is extremely critical. If only the nodes with the maximal residual energy are chosen as CHs, the following issues arise.

(1) After the system is initialized and deployed, the energy consumption of each node may be randomly changed due to the related factors such as the corresponding service and location of nodes. Therefore, the energy consumption of each node may vary greatly. Furthermore, CHs may be distributed unevenly in underwater regions. The number of nodes managed by a CH may be extremely large, while nodes managed by another CH may be rare. There may be isolated nodes that cause the black holes of coverage in an UASN.

(2) It is generally accepted that the random deployment obtains a relatively uniform distribution of nodes. If clustering mechanisms are implemented, there will be multiple clusters of different scales appeared. It can be observed that the energy of CHs with a large number of CMs will be quickly exhausted. AS the CH is exhausted, the corresponding cluster will be disbanded, so the clustering process will be implemented continuously. This will greatly decrease the survival time of UASNs.

(3) Assuming the same residual energy of some CMs, the probability that all nodes are chosen as a CH is equal. Therefore, a large number of nodes far away the BS or surface sink node will be elected as CHs. This will result in a non-optimal path. It is disadvantageous for data forwarding, which increases the delay of transmission significantly. Especially in large-scale long-distance UASNs, the defects of compromised clustering will be particularly prominent. On the other hand, if a large number of CMs rely on nodes close to the sink or BS as CHs, it will cause these elected CHs to run out quickly and become bottlenecks of networks.

To solve the issues mentioned above, this paper presents a clustering algorithm based on 3D mesh. The main contribution involves the following parts. Firstly, design a hierarchical network architecture and an energy consumption model of UASNs. Secondly, introduce the clustering mechanism, which includes the basic clustering packets, the setup phase and the data transmission phase. Thirdly, do experiments based on WOSS and MATLAB, and compare our algorithm with DS-VBF, IAR, and GEDAR on the average end-to-end delay, the survival rate, the number of survival nodes, the number of clusters, and the coverage ratio.

The layout of the paper is outlined as follows. Section 2 provides an overview of the related works. Section 3 describes the system structure. Section 4 presents the clustering algorithm. The simulation is exploited in section 5. Finally, we conclude the paper.

2. RELATED WORKS

Considering energy savings and other factors, clustering-based routing techniques have received extensive attention. LEACH [6] (Low-Energy Adaptive Clustering Hierarchy) is a clustering algorithm, in which an UASN is divided into multiple units (clusters), and each consists of a CH and numerous CMs. The election of CHs is accomplished through presetting or adopting an appropriate mechanism. However, unique upward or downward transmission direction between sink nodes and CHs is not considered. In addition, it is assumed that the energy consumption of CHs is uniform, which has a definite gap with the actual applications. Dipanwita [7] *et al.* propose a clustering algorithm (GEDAR for short) based on 3D mesh. In this algorithm, an UASN is regarded as a BC (Big Cube), and each cluster is divided into multiple SCs (Small Cubes). CHs are elected by comparing the preset threshold of residual energy and the probability that a node is set to CH. At last, CHs aggregate data, and apply the multi-hop routing.

Maryam [11] *et al.* introduce DS-VBF (Dual Sinks Vector-Based Forwarding). It takes both residual energy and location information as priority factors to discover an optimized routing path in underwater networks. It employs dual sinks on the ocean surface, and forms the optimal clusters by balancing the maximal residual energy and location information of nodes. Ariona [12] *et al.* propose a collision-aware-based clustering protocol (IAR). It is a centralized cross-layer solution. The authors design a class of scheduling and routing policies supporting for power controlling, which assign each node an optimal transmission time, forward link and transmission power level for reliable communication. Simulation shows that IAR improves the energy consumption and the throughput significantly. Rodolfo [13] *et al.* propose GEDAR (Geographic with Depth Adjustment Routing), which is a unicast, geographic and opportunistic routing algorithm in UASNs. Experiments show that GEDAR improves the network performance significantly when compared with the baseline solutions, even in hard and difficult underwater scenarios.

3. SYSTEM STRUCTURE OF UASNS

3.1 UASN Structure of Hierarchical 3D Mesh

In this paper, an UASN is deployed in a hierarchical 3D model, as shown in Fig. 1. Based on this structure, an UASN is divided into *n* layers, nodes of each layer form a cluster. The clustering algorithm selects CHs based on the location of nodes in the cluster. The horizontal link is used for communication between clusters. CHs collect and aggregate data of CMs in the same clusters, and transmit data to the neighbor CHs that towards to the surface sink by the vertical links.

In this work, nodes are deployed in a densely manner. And the network is divided into multi 3D meshes. The IDs of mesh are numbered in Fig. 2. To this end, a two-level addressing method is proposed. Among them, CHs and CMs all use a 32-bit local address for the intra-cluster communication. The address format is $\langle grid.X.Y.Z\rangle$, where *gridID* represents a mesh ID of which CMs belongs to, and $\langle X,Y,Z\rangle$ the position of 3D mesh. The addressing range in a cluster is 0.0.0.1 to 254.255.255.254. The *gridID* which exceeds 255, are reserved by CHs. The inter-cluster communication uses a 2D plane, so the format of the address is ⟨255.*gridID.X.Y*⟩. The accuracy of data aggregation depends on the deployment density of UASNs.

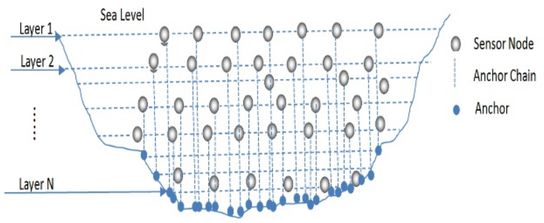

Fig. 1. The hierarchical network model.

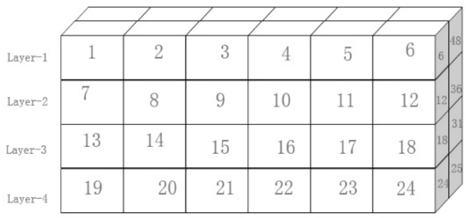

Fig. 2. The mesh number of 3D UASNs.

3.2 The Energy Consumption Model

The survival time of UASNs depends on the energy consumption of underwater nodes. To obtain energy consumption, Urick model [14] is used in this paper. The passive sonar equation listed in Eq. (1) quantifies the signal-to-noise ratio (SNR) of UASNs from source to destination.

$$DT = SL - TL - (NL - DI) \tag{1}$$

Where *SL* denotes the sound source level, *TL* the transmission loss, *NL* the noise level, and *DI* the directivity index. Let $N_t(t)$ represent turbulence noise, $N_s(t)$ the ship noise, $N_w(t)$ the wind noise, and $N_h(t)$ the thermal noise. A given frequency is denoted by $f(t)$. The energy spectral density [15] of the four noise is shown in Eq. (2).

$$\begin{aligned} &10\lg N_t(t) = 17 - 30\lg f(t) \\ &10\lg N_s(t) = 40 + 20(s - 0.5) + 26\lg f(t) - 60\lg(f(t) + 0.03) \\ &10\lg N_w(t) = 50 + \frac{7.5}{2} w + 20\lg f(t) - 40\lg(f(t) + 0.4) \\ &10\lg N_h(t) = -15 + 20\lg f(t) \end{aligned} \tag{2}$$

Therefore, $N_{Total}(t)$, the energy spectral density of noise is shown in Eq. (3).

$$N_{Total}(t) = N_t(t) + N_s(t) + N_w(t) + N_h(t) \tag{3}$$

At different frequencies, the influence of each component on energy spectral density of noise is also distinctive. The communication frequency used in this paper is 10 KHz, and factors that affect the frequency are attenuation, communication distance and propagation delay. Assuming that a node is omnidirectional, so the value of the directionality index *DI* is 0. Combining the absorption effect with the dissipation loss, *TL* is shown in Eq. (4).

$$TL = k \times 101\text{g}d + d \times 101\text{g}\alpha(t) \tag{4}$$

Where the first part represents the propagation loss, *k* the propagation coefficient of the geometric model [16-18] ($k=1$ represents a cylindrical structure, $k=2$ a spherical structure, $k=1.5$ the actual propagation structure), and d the distance. The definition of the absorption loss is shown in Eq. (5).

$$10\lg\alpha(t)=\begin{cases}\dfrac{99t^2}{820\times(1+t^2)}+2.74\times10^{-4}t^2+0.003 \\ \qquad t\geq 0.4 \\ \dfrac{0.11t}{1+t}+0.011t+0.002 \\ \qquad t<0.4\end{cases} \tag{5}$$

At the receiver, define a target SNR as 15dB. The value of SL is obtained from Eq. (1), let I_t be the strength of the signal transmitted, and I_t is shown in Eq. (6).

$$I_t = 10^{SL/10} \times 0.67 \times 10^{-18} \tag{6}$$

Then P_t, which denotes the energy of a bit transmitted is showed in Eq. (7), where h the depth of the node deploy in the water.

$$P_t = 2 \times 3.14 \times h \times I_t \tag{7}$$

The energy consumption is estimated based on Urick model. Assuming that the energy consumption of receiving is 1/5 of that transmitting, each control packet is 16 bytes, and each data packet is 80 bytes. CHs collect data from CMs and then perform aggregation to facilitate the extraction of related data. In addition, data received by CHs need to be compressed before being sent. E_{CM}, which means the energy consumption of CMs, is showed in Eq. (8).

$$E_{CM} = E_{Setup\_CM} \times E_{Data\_CM} \tag{8}$$

Where E_{Data_CM} means the energy of data transmission, E_{Setup_CM} the energy consumption for the setup phase. E_{Setup_CM} is shown in Eq. (9), where $Rev()$ represents the receiving function, $Tran()$ the sending function, and P_{tCM} the transmission energy of a CM.

$$E_{Setup\_CM}=\frac{P_{tCM}}{f(t)}\times\begin{pmatrix}Rev\left(CM_{ADV\text{-}MSG}\right)\\ +Tran\left(CM_{JOIN-MSG}\right)\\ +Rev\left(CM_{START-MSG}\right)\end{pmatrix} \tag{9}$$

The energy consumption of E_{Data_CM} is shown in Eq. (10).

$$E_{Data\_CM}=\frac{P_{tCM}}{f(t)} \tag{10}$$

Compared with the energy consumption of a CM, the energy consumption of a CH is showed in Eq. (11).

$$E_{CH} = E_{Setup\_CH} \times E_{Setup\_CH} \times E_{inter\_CH}. \tag{11}$$

Where E_{Setup_CH} denotes the energy consumption for the configuration phase, E_{Data_CH} the energy consumption of transmission, and E_{inter_CH} the energy consumption of traversing the intermediate CHs. E_{Setup_CH} is shown in Eq. (12), in which P_{tCH} represents the energy consumption of transmission for a CH in a mesh.

$$E_{setup\_CH} = \frac{P_{tCH}}{f(t)} \times \begin{pmatrix} Tran(CH_{ADV-MSG}) \\ +\sum_{i=1}^{n} Rev(CH_{JOIN-MSG}) \\ +Tran(CH_{START-MSG}) \end{pmatrix} \tag{12}$$

Since a CH communicates with CMs in a cluster, the energy consumption E_{Data_CH} for data transmission is shown in Eq. (13).

$$E_{Data\_CH} = \frac{P_{tCH} \times \sum_{i=1}^{n} Rev(Data_i)}{f(t)} \tag{13}$$

When transmitting data to the surface sink, it may be necessary to traverse multi CHs. Therefore, E_{inter_CH}, which represents the energy consumption of traversing multi intermediate CHs is showed as Eq. (14).

$$E_{inter-CH} = \frac{\sum_{i=1}^{n} P_{tCH}}{f(t)} \times \begin{pmatrix} Tran(Data_i) \\ +Rev(Data_i) \end{pmatrix} \tag{14}$$

4. A CLUSTERING ALGORITHM BASED ON HIERARCHICAL 3D MESH

4.1 Basic Clustering Messages

This paper proposes a clustering algorithm based on hierarchical 3D mesh, by which to shorten the data transmission distance. The problem of excessive energy consumption of CHs is mitigated by rotating CHs within the 3D mesh, and the stability of the cluster is improved. In an UASN, there are numerous 3D meshes, in which CHs are selected cyclically. Although multiple nodes can be set as CHs in a mesh, only one CH is elected in a cycle, and other nodes set to CMs. The election mainly refers to the residual energy and memory of these nodes.

The clustering algorithm consists of two steps, which are set-up and transmission. In the setup phase, all CHs can be elected, and each cluster will be formed. Multiple CHs guarantee the system reliability and load balancing. These CHs can communicate with CMs in a cluster to save energy. Followed by is the data transmission phase, in which all CMs transfer data to the respective CHs, and the relative CHs will receive, check and merge the data, then transfer them after compression. In some cases, the data should be encrypted. In the data transmission phase, CHs deliver aggregated data to the neighbor CH node towards the surface sink in multi-hop mode. The packets used for clustering is listed in Table 1.

Table 1. The related packets.

Packets	Function
Hello	A Sink node broadcasts this message. The weight of competing CH is calculated by the HELLO message.
Cluster_Head	The node sends the message to compete for the cluster head.
Join_Cluster	A CM uses this message to request for joining a cluster.
Schedule	A CH broadcasts this message to all CMs in a cluster for task scheduling.
Route_Request	A CH node sends this message to the corresponding neighboring CH nodes for routing request.
Route-Response	A CH node reply the Route_Request of its' neighboring CH nodes.

4.2 The Clustering Setup Phase

Assuming that n nodes deploy randomly, three distinct location anchors set at the bottom of oceans, and the location of anchors is already known. All nodes suspend at different depths by anchors connected to buoy or floats. Each node equips with a random depth gauge, which stretches the anchor chain according to a preset depth. The anchor sinks into the bottom of oceans, and all sensors equip on a buoy or a surface float. The sink nodes which energy by specific devices, are fixed at the center of the surface. Each node has a unique ID and is energized by battery. Once the energy is exhausted, a node is discarded. Assume that the relative motion of the underwater nodes is not large. The phase of clustering setup lists as follows.

(1) Once an UASN is deployed, the initial value of each mesh is preset. Each node relies on the three location anchors to obtain its position <x, y, z> quickly. Combined with its location message and preset 3D mesh, a node can learn the mesh that it belongs to quickly. Therefore, after the system is initialized, the corresponding mesh ID is acquired.

(2) After the calculation is complete, the sink node broadcasts Hello packets to all nodes in a 3D mesh, which contains the CH election threshold T_{CH}. Once node i receives a Hello packet, it immediately enters the CH election phase. The node will calculate the distance $d\langle i, Sink\rangle$ between it and the surface sink node according to the signal strength of the Hello packet, and count the CH election weight $W_{Cluster\_Head}(i)$, which is calculated in each round. $W_{Cluster\_Head}(i)$ is shown in Eq. (15).

$$W_{Cluster\_Head}(i) = \alpha \left\lfloor \frac{d\langle i,\ Sink\rangle}{d_0} \right\rfloor + \frac{(1-\alpha)E_{residual}(i)}{E_0} \tag{15}$$

Where α represents a weighting factor and d_0 the preset optimal transmission distance. For the convenience of calculation, d_0 refers to the distance from the center position of a 3D mesh to the sink node. For instance, in a 3D mesh of $a \times b \times c$, the optimal transmission distance d_0 is defined as follows.

$$d_0 = \frac{\sqrt{a^2 + b^2 + c^2}}{2} \tag{16}$$

Where a, b, c represent the position of length, width and height for a node in a 3D mesh. If $W_{Cluster\_Head}(i)$ of node i is greater than the election threshold T_{CH} of CH, this node will set itself to TH (Temporary Head) role, otherwise it will be set to CM role.

(3) The TH node will count the waiting time $T_{Wait\_cluster}(i)$ for CH competition. If none of Cluster_Head packets sent by other CHs is received in $T_{Wait\_cluster}(i)$, then, the TH node competes for CH role successfully and broadcasts a Cluster_Head packet to all nodes in the 3D mesh which is centered on it. The waiting time for node i is shown in Eq. (17):

$$T_{Wait\_cluster}\left(i\right)=\frac{kT_{Cluster\text{-}compete}}{W_{Cluster\_Head}\left(i\right)}. \tag{17}$$

Where $T_{Cluster\text{-}compete}$ denotes the time spent in CH election in a single cycle, and k the execution turns. In the system initialization phase, since the number of nodes survives is large, a CH can be elected quickly, so the weight of k can be relatively small. In transmitting phase, the energy of some nodes exhausted, and the election time of CH can be extended by increasing the number of rounds, that is, increasing the value of k.

(4) When a TH node i receives the Cluster_Head packet sent by node j, and the election weight $W_{Cluster\_Head}(j)$ is greater than i, then node i will update its role to CM, and receives the Cluster_Head packet in the range of the 3D mesh centered on it continuously until the end of $T_{Cluster\_compete}$.

(5) In a 3D mesh, if a CM never receive a Cluster_Head packet at the end of $T_{Cluster\_compete}$, it will set its role to CH, and broadcast a Cluster_Head message in the 3D mesh centered on itself with the communication radius $R_{Cluster\_head\_compete}(i)$. At this time, other THs that receive Cluster_Head packets will change their role to CMs for avoiding coverage overlap. The $R_{Cluster\_head\_compete}(i)$ is shown in Eq. (18).

$$R_{Cluster\_head\_compete}(i)=\frac{(d\langle i,Sink\rangle-d_{\min})\times E_{Resldual}(i)}{(d_{\max}-d_{\min})\times E_0}\times R_{pre-set} \tag{18}$$

Where $d_{\max}$ and $d_{\min}$ represent the farthest and closest distances of a sink node to the 3D mesh respectively, $R_{pre\text{-}set}$ the preset broadcast radius, $E_{Resldual}(i)$ the residual energy, and E_0 the initial energy.

(6) Set the interval T_{member_join} on the CH as the time schedule for CMs to join, each CM will select a CH closest to itself, and send a Join_Cluster packet. If a CM is at the border of two or more 3D mesh, then the CM will join a cluster with the smallest ID number preferentially.

(7) After the interval T_{member_join} which is set for CMs to join a cluster ends, a CH divides the transmission time slots according to the number of CMs register in the corresponding cluster, and notifies all CMs by broadcasting a Schedule packet. The scheduling can be performed based on related methods such as TDMA (Time Division Multiple Access) and STDMA (Space Time Division Multiple Access). The pseudo code of the clustering setup phase is shown as follows.

Algorithm 1: The clustering setup phase

Start
for ($i = 0$, $i \le Node_{count}$, i++)
for($j = 0$, $j < Cluster_{count}$, j++)
{
Initialze node(i);
Role-node(i) = cm;
Vol_unit_3D = k; //preset volume of 3d mesh
$i \in Cluster_{count}$;
Cluster_ID(Node(i)) = Mesh_id(j); // Calcute id of 3d mesh
Cluster_position(Node(i)) = Mesh_position(j); // Calcute id of 3d mesh
Node(i) Broadcast Hello;
if ($Node(i)$) < T_c)
{
$Compute(d_0)$;
$W_{Cluster\_Head}(i) = \alpha \left[\frac{d\langle i,\ Sink\rangle}{d_0} \right] + \frac{(1-\alpha)E_{residual}(i)}{E_0}$;
if ($W_{Cluster\_Head}(i) > TH_{Cluster}$)
{
Role_node(i) = TH;
$T_{Wait\_cluster}(i) = \frac{kT_{Cluster\text{-}compete}}{W_{Cluster\_Head}(i)}$;
if ($T_{Wait\_cluster}(i) < T_{Cluster\text{-}compete}$)
{
is (Cluster-Head_Received) = False;
Role_node(i) = CH;
Broadcast CLUSTER_HEAD(i);
}
else if ($W_{Cluster\_Head}(k) > W_{Cluster\_Head}(i)$)
{
Role_node(i) = Cm;
Role_node(k) = CH;
}
else{
Role_node(i) = th;
$R_{Cluster\_head\_compete}(i) = \frac{(d\langle i, Sink\rangle - d_{min}) \times E_{Residual}(i)}{(d_{max} - d_{min}) \times E_0} \times R_{pre-set}$;
}
if ($T \ < T_{member\_join}$){
Join(Node(i+1)); //Node(i) join to a cluster;
Schedule(Node(i));
}
else
{
Role_node(i) = CH;
}
}
$i = i + 1$;
}
}
End

4.3 Data Transmission Phase

After the setup phase is completed, data transmission phase can be performed. The data transmission phase can be divided into intra-cluster communication and inter-cluster communication two parts. During intra-cluster communication, all CMs in a cluster will send data to its CH directly. After receiving data, the CH performs verification, compression, encoding, and encryption. Then CH stores them in the queue of corresponding data group to be sent. After that, the CH sends a Route_Request packet to the neighboring CHs for constructing the routing path, through which it can transfer data to the sink node. During inter-cluster communication, a CH has to find the best path to the sink node according to the path weight. The process for a CH finds the optimal paths towards to a sink node lists as follows.

(1) A source CH i first determines its routing interval $T_{Route\text{-}preset}$ and then defines the temporary routing weight $W_{Temporary\_route}(i)$, which is shown in Eq. (19).

$$W_{Temporary\_route}(i) = \eta \frac{E_{\mathrm{Re}sidual}(i)}{E_0} + \frac{(1-\eta)}{Count_{CMs}(i)} \tag{19}$$

Where η denotes the weight factor defined by the energy ratio and $Count_{CMs}(i)$ the number of CMs in a cluster. The CH i broadcasts $W_{Temporary\_route}(i)$ to all CHs of neighboring CHs through Route_Request packets.

(2) After receiving the Route_Request packet sent by CH i, the neighbor CH j will count the transmission distance $d\langle i, j\rangle$ from i according to the signal strength of Route_Request message. If $d\langle i, j\rangle$ is greater than the preset distance threshold d_0, $W_{Temporary\_route}(i)$ of CH i is taken as the formal routing weight $W_{Formal\_route}(i, j)$. Otherwise, $W_{Temporary\_route}(i) + 1$ is taken as the formal routing weight. $W_{Formal\_route}(i, j)$ is sent to node i via Route-Response packets until the routing interval ends. $W_{Formal\_route}(i, j)$ is shown in Eq. (20).

$$W_{Formal\_route}(i, j) = \begin{cases} W_{Temporary\_relay}(i), & d\langle i, j\rangle > d_0 \\ W_{Temporary\_relay}(i) + 1, & d\langle i, j\rangle d_0 \end{cases} \tag{20}$$

(3) Since each CH sends a Route-Request packet to multiple neighboring CHs, multiple Route-Response packets are received as well. Supposing that CH i obtains the routing weights set $\{W_{Formal\_route}(i, x_1), W_{Formal\_route}(i, x_2), \ldots, W_{Formal\_route}(i, x_n)\}$, in which x_1, x_2, …, x_n represents n adjacent CHs of i from multiple 3D mesh. The CH i needs to sort the routing weights set, and records the neighbor CHs with the largest routing weight in its routing table. Then takes them as the next hop. If there are multiple CHs with the same routing weight, the CH which closer to the sink node is priority selected. If the distance is the same, the CH with the smaller ID will be selected.

(4) At this time, CH i will perform data transmission. First, it needs to compare whether the distance $d\langle i, Sink\rangle$ from it to the sink node is greater than the preset distance threshold $TH_{Distance\_preset}$. If so, the neighboring CH with the largest routing weight is selected

as the next hop, and the multi-hop transmission for the sink node is implemented sequentially. Otherwise, the data is sent to the surface sink directly.

(5) Each node of a cluster will continue to transmit data in turns. When a round end, the system is re-initialized. The process is repeated until all nodes are exhausted. The data transmission phase is illustrated in Fig. 3.

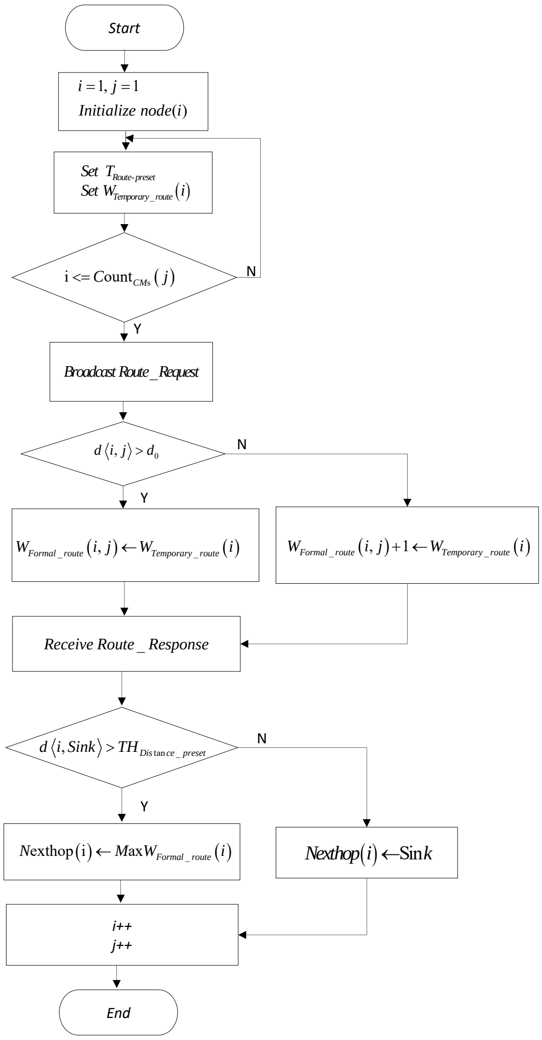

Fig. 3. The data transmission phase.

5. SIMULATION

The simulation is performed to reveal the potential advantages of our algorithm by comparing with DS-VBF, IAR and GEDAR. A marine testbed is built based on WOSS

[19-20] and the simulation runs on MATLAB. The optimal horizontal transmission distance is set to 100m, and the vertical transmission distance 500m. The volume of each mesh is set to $30\times40\times500m^3$. The experiment is executed more than 100 rounds. Other relevant parameters list in Table 2.

5.1 The Average End-To-End Delay

Due to clustering, the multi-hop relay method is used to transmit data. For this reason, the average end-to-end delay of the four algorithms is discussed. Considering that the influence of tides and currents varies in the oceans, the noise threshold is uniformly given for comparative analysis. The simulation is performed more than 1000 minutes. Fig. 4 shows the comparison results. As the simulation continues, the delay gradually decreases. At the end of the simulation, the delay of our algorithm converges to 33ms, while DS-VBF 39ms, IAR 63ms, and GEDAR 78ms.

Table 2. Simulation parameters.

Parameter	Value	Parameter	Value
Channel Type	Rayleigh	Noise Type	Complex Gaussian
Carrier frequency	10 KHz	Update interval	150 ms
Range of 3D Mesh	$30\times40\times500m^3$	Number of layers	5
Initial energy of node	1000 J	Energy of Transmitting	50 J
Energy of Receiving	10 J	Energy of Sleeping	3 J
Guard interval	120 ms	Max multipath delay	40 ms
Configuring times	150 ms	Depth	500 m

5.2 The Survival Rate of UASNs

As a key indicator, survival time is used to measure the energy consumption of UASNs. With the operation of the system, the nodes will fail due to the energy exhaustion. Therefore, the network lifetime can be obtained by count the survival rate. Fig. 4 shows the simulation results. By comparison, it can be seen that the survival rate of our algorithm is relatively high, after executing 100 rounds, there are still 55% of nodes alive. However, that of GEDAR is slightly higher, which are 65%, the IAR 40%, and the DS-VBF 20%.

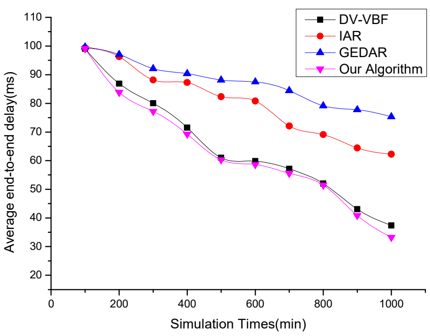

Fig. 4. Average end-to-end delay comparison.

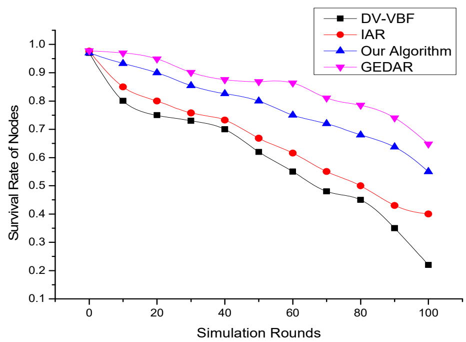

Fig. 5. The comparison of network lifetime.

Fig. 5 shows the average surviving nodes of the four algorithms under 10 different deployment densities. The initial deployment density is 28, which is reduced in turns, and the final value is 10. From the experiment, we know that the average surviving nodes of GEDAR is highest, our algorithm closes to GEDAR, and IAR is lower than our algorithm, while DV-VBF algorithm is the lowest. However, our algorithm is most sensitive to the deployment density of nodes.

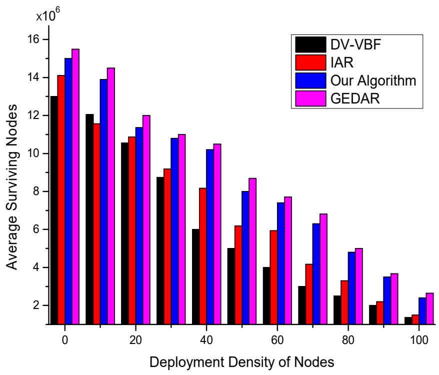

Fig. 6. the average survival nodes.

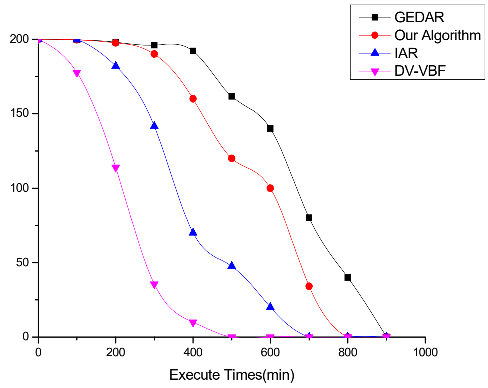

Fig. 7. the comparison of surviving nodes.

5.3 The Number of Survival Nodes

Underwater nodes are powered by battery. As the systems are working, nodes will run out and die gradually. The more the number of surviving nodes in the same period, the lower energy consumptions. Fig. 7 is the comparison of the surviving nodes under the four algorithms. It can be observed that the surviving nodes of IAR and DV-VBF are lower than that of our algorithm, and that of GEDAR is highest.

In GEDAR, the multi-hop relay method is used to switch the transmission mode of CHs based on the energy level. Therefore, survival nodes are relatively large. Since our algorithm has similar functions with GEDAR, and implements such an energy saving mechanism that a node is set to sleep mode when it is idle. As a result, the energy consumption is close to GEDAR. However, in DV-VBF all nodes are always in active mode, the energy consumption is rapid. In addition, in IAR, CHs change continuously, so the survival nodes decrease sharply.

5.4 The Number of Clusters

Considering the differences of the network topologies based on the random deployment of underwater nodes, deployments are performed 10 times, and the experiment of each deployment is taken notes, as shown in Fig. 8. Through statistics, we know that the more CHs, the denser clusters are built, and clusters constructed by the four algorithms in different rounds are distinctive. The number of CHs in our algorithm is small, and that in GEDAR is relatively large. The maximum number of CHs constructed in our algorithm is 12, and the minimum number is 6.

5.5 The Coverage Ratio of Clusters

The coverage ratio of the clusters is related to the intensity of the unit cluster elements constructed and node deployments that are built. Under initial conditions, an UASN is a dense type, and as the node dies, the system may become sparse type. At this point, it happens that some nodes may not be in any cluster, which will result in isolated nodes. If a large number of isolated nodes appear in an UASN, it means that a large area is not covered. In the same network topology, the higher the coverage rate, the better the accessibility of the route is guaranteed. Fig. 9 shows the coverage ratio of the four algorithms. It can be seen that the coverage ratio of our algorithm is relatively high, which greatly guarantees the implementation of routing.

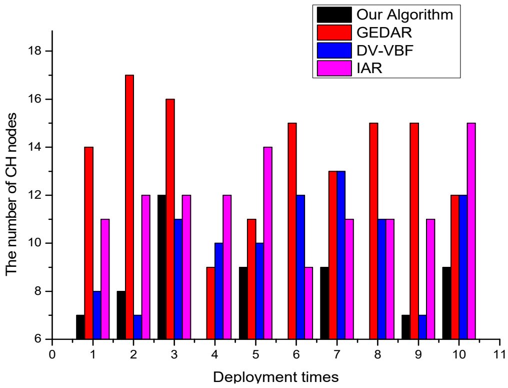

Fig. 8. the number of CHs.

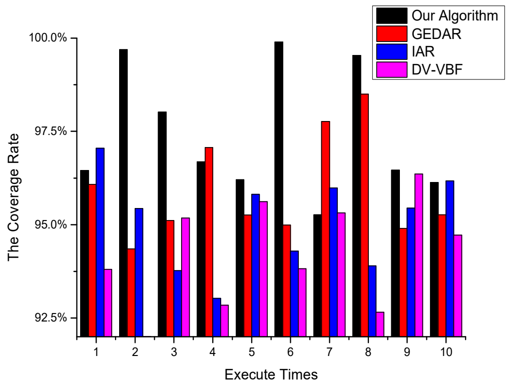

Fig. 9. the cluster coverage rate.

6. CONCLUSIONS AND FUTURE WORK

This paper proposed a clustering algorithm based on hierarchical 3D mesh for underwater acoustic sensor networks. The algorithm was compared with DS-VBF, IAR, and GEDAR. The simulation showed that the average end-to-end delay of the proposed algorithm was the shortest one. After a long period, the survival rate of the network was relatively high, indicated that the algorithm had a longer network life cycle. Therefore, a tradeoff between the delay and the network survival time was achieved. However, the influences of ocean currents, the movement of the nodes, different ultrasonic frequency settings and other factors were not considered. All these will be the primary content of further study. We are now focusing on assessing the performance statistics by employing a variety of bionic-based clustering algorithms (such as the ant colony, firefly, and bee algorithms) in UASNs. The next work is to improve the performance of clustering by constructing virtual MIMO nodes and incorporating cross-layer optimization technology.

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