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# An Energy Optimization Clustering Scheme for Multi-Hop Underwater Acoustic Cooperative Sensor Networks

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**ABSTRACT** In this paper, we propose an improved energy optimization clustering algorithm (EOCA) for the multi-hop underwater acoustic cooperative sensor networks (UWA-CSN) due to the limited energy supply of the underwater sensor nodes. The proposed EOCA scheme considers multiple factors, such as the number of neighbor nodes, the residual energy of each node, the motion of the sensor nodes caused by the ocean currents, and the distance between the sink node and each underwater sensor node. All these factors are considered within the framework of the multi-hop cooperative communication. Moreover, in the proposed energy optimization scheme, we define a residual energy based maximum effective communication range (reE-MECCR) according to the residual energy of each underwater sensor node, which can adaptively control the energy consumption of data transmission for each hop. Compared with the existing clustering scheme, the experimental results demonstrate that the proposed EOCA scheme can not only prolong the life time of the multi-hop UWA-CSN, but also keep a good communication and networking performance, including the package delivery ratio, the energy consumption efficiency, and the network coverage area. The proposed scheme can obtain both the clustering benefit and the cooperative communication benefit for the multi-hop UWA-SN in terms of energy saving in underwater environments.

**INDEX TERMS** Underwater acoustic networks, cooperative communications, clustering algorithm, energy optimization.

## I. INTRODUCTION

In recent years, with the invention of the advanced hardware equipment and the efficient communication protocols, the underwater wireless sensor network has made great progress and attracted more and more researchers' attention [1]. In addition, because of the growth of the wide application demands, such as the environmental monitoring, pollution control, disaster forecast and military activities [2], [3], [4], the number of related studies about the underwater wireless sensor networks is gradually increasing. There

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also have already been some applications of the underwater wireless networks, such as the Seaweb underwater acoustic networking in the US [5] and the NEPTUNE underwater acoustic networking in Canada [6]. The persistent littoral undersea surveillance network (PLUSNet), supported by office of naval research (ONR) of the US, demonstrates multi-sensor and multi-vehicle anti-submarine warfare (ASW) by means of the underwater acoustic communications network [7].

In underwater environments, the electromagnetic wave signal will be affected by the strong attenuation caused by the propagation medium. Fortunately, by using the acoustic wave, we can achieve a reliable data transmission over a long

distance at a relative low frequency [8]. However, due to the high complexity of the underwater environment and the slow propagation speed of the underwater acoustic wave, there are still lots of problems about the quality of the communication need to be solved, such as limited frequency bandwidth, long communication delay, and so on. Furthermore, the cost of energy resource is high in order to maintain a good communication performance for the underwater acoustic sensor networks (UWA-SN). However, in practice, the energy supply of the underwater sensor nodes is limited, and it is difficult to charge or replace it, which requires large amount of man power and money [9], [10].

To improve the reliability of the communication, the cooperative communication technology in multi-hop underwater acoustic cooperative sensor networks (UWA-CSN) is adopted, in which the end to end communication over long distance is assisted by relay nodes [11]. In order to solve the problems of data transmission collision and load balance for the multi-hop UWA-CSN, it is necessary to construct a reasonable network topology. At present, some studies have demonstrated that using clustering technology can improve the communication performance, as well as the energy consumption for the UWA-SN [12], [13], [14]. Through the clustering technology, the underwater sensor nodes in a network will be divided into several subsets called clusters, and these clusters may be almost independent with each other. Then in each cluster, the data is collected and combined by the cluster head (CH) node and finally sent to the sink node or base station by the CH node. As far as we know, the research on the clustering algorithm for the multi-hop UWA-CSN is still scarce. The energy optimization for the UWA-CSN is one of the most efficient ways to prolong the network lifetime. Therefore, motivated by the existing works, we consider adopting the clustering technology to realize the energy optimization for the multi-hop UWA-CSN.

In this paper, we propose an improved energy optimization clustering scheme for the multi-hop UWA-CSN, by which we hope the multi-hop UWA-CSN can keep a good communication performance, and achieve the goal of a long life time by energy consumption optimization. As a frontier research on designing a clustering scheme for the UWA-CSN to solve the energy optimization problem, the main contributions of this paper can be summarized as follows:

(1) In the multi-hop UWA-CSN model, we introduce the motion of the underwater sensor nodes caused by the ocean current, which is very common in practical complex marine environments. The presented drifted model of the underwater sensor nodes in this paper is referenced from [41].

(2) We proposed an energy optimization clustering algorithm (EOCA) for the multi-hop UWA-CSN motivated by the cluster-based mobile data gathering (CMDG) scheme in [34]. In the CH nodes selection process of the proposed algorithm, we consider several factors such as the number of neighbor nodes, the residual energy and the distance to the sink node for each underwater sensor node. Furthermore, since the cooperative strategy was considered to obtain the

cooperative gain and save the energy consumption in each cluster, we design the clustering algorithm by considering the cooperative transmission mode in each cluster. The feasibility and benefit of underwater acoustic cooperative strategy has have been verified in our previous work [37] in a sea trail in Taiwan Strait, and cooperative strategy in underwater acoustic communications is indeed well recognized and adopted [42], [43].

(3) In order to control the energy consumption of data transmission for each hop, we introduce the arctangent function to build a residual energy based maximum effective communication range (reE-MECCR) scheme in the energy optimization process for each underwater sensor node, which can adaptively set the proper maximum effective communication range (MECCR) according to the residual energy of each underwater node. This will be more energy efficient compared with the existing *fixed* MECCR scheme in [34].

(4) We compare the performance of the proposed EOCA scheme with the existing clustering algorithm, and analyze the influences of the network coverage area and the number of underwater sensor nodes on the proposed scheme.

The rest of this paper is organized as follows. In Section II, we give out the related work about the clustering algorithm for the UWA-SN. The related models mentioned in this paper are introduced in Section III. In Section IV, we present the proposed EOCA scheme for the multi-hop UWA-CSN. The simulation results are shown in Section V. Finally, we make a conclusion in Section VI.

## II. RELATED WORK

We firstly introduce some characteristics of the UWA-CSN. In the UWA-CSN, there exist some nodes called cooperative nodes, which can help other nodes transmit data. More specifically, the receiver can receive the signals from the sender and the cooperative node at the same time forming a cooperative gain. In this way, a longer transmitting distance and a more reliable communication can be achieved. This is also the main difference between the UWA-CSN and the UWA-SN. So far, there have been some researches on the UWA-CSN. In [15], Jae *et al.* proposed an efficient cooperative automatic repeat request scheme which can improve the throughput in the network. In [16], we proposed a node cooperation protocol and studied the data collection efficiency of the different data collection paths. In [17], Yen-Da et al. designed a self-adaptive cooperative routing protocol which can improve the end-to-end delay and packet delivery ratio.

Since there are no studies on the clustering algorithm for the UWA-CSN, we mainly introduce the related researches on the UWA-SN in the next. At present, the clustering algorithms proposed in the field of terrestrial wireless communication, such as the low energy adaptive clustering hierarchy (LEACH), the hybrid energy-efficient distributed clustering approach (HEED), the geographical adaptive fidelity (GAF) and so on, have shown their excellent performance in reducing the collision and improving the throughput [18], [19], [20]. However, in the UWA-SN, the communication

delay is relative long, and the nodes under the water only possess limited energy. What's worse, the underwater nodes are hardly located accurately using the GPS. As a result, the above clustering algorithms in the terrestrial wireless communication are not directly applicable for the UWA-SN. Therefore, it is important to design a reliable and effective clustering algorithm according to the characteristics of the UWA-SN. In [21], Sundarameena *et al.* presented a clustering algorithm based on the 3D grid structure, which separates the whole network into several grids, and selects the CH nodes through the periodic dormant-wake mechanism; Then, the non-cluster head (nCH) nodes make a connection with the CH nodes using the broadcast information sent by the CH nodes and eventually form the cluster structure for the UWA-SN. In [14], in order to make the GAF algorithm suitable for the underwater environment, Liu *et al.* proposed the a improved GAF algorithm, called the based on the GAF (BGAF) algorithm, to solve the energy hole problem caused by the CH nodes constantly transmitting data by considering the residual energy of each node in the CH nodes selecting process. In [22], Zhang *et al.* designed an improved clustering algorithm based on the K-means algorithm, in which the node density of the UWA-SN and the depth of the underwater node have been considered, to overcome the disadvantages of the original algorithm such as the cluster structure instability, the high energy consumption and computation complexity. In [23] and [24], the authors proposed two different improved LEACH algorithms to solve the strong randomness and data transmission collision problem of LEACH algorithm in the terrestrial wireless network. The former reduces the randomness of the CH nodes selection by decreasing the number of updated nodes in each status updating period and marking the nodes already be the CH node before. The latter solves the data transmission collision problem by establishing a slot table for each CH node, which can avoid the situation that each nCH node might receive several broadcast information at the same time. In [25], Wang *et al.* proposed a clustering algorithm based on 3D mesh in order to improve the survival time and end-to-end delay performance. In [26], Bandita *et al.* introduced a supporting cluster head for each cluster to avoid the data loss and increase the fault tolerance. In [27], Robert *et al.* proposed a novel clustering algorithm called the murmuration inspired clustering algorithm, which can improve the network lifetime by reducing the unnecessary overhead. In [28], Yang *et al.* designed a clustering protocol to enhance the security of the UWA-SN. The above literatures mainly focus on the non-cooperative underwater acoustic sensor network, and have ignored the motion of the underwater sensor node caused by the ocean current in practice.

Next, we introduce some studies on the energy optimization using clustering algorithm for the UWA-SN. In [29], Vani *et al.* proposed to use the geographic location to establish the clustering structure of UWA-SN, and respectively adopt the fuzzy logic algorithm and the particle swarm optimization in the clustering process and the CH nodes selection process.

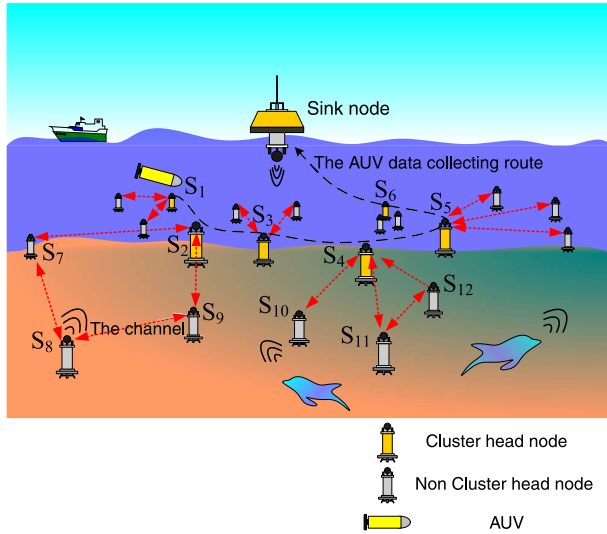
The experimental result showed the superior performance of the proposed method in the energy optimization. However, it is really difficult to obtain the precise location information in the underwater environment. In [30], Ahmed *et al.* proposed to reduce the system energy consumption by using the region node and the CH node to control the redundant transmission. Furthermore, they considered the motion of the underwater node caused by the ocean current in their study. In [31], Li *et al.* designed an improved clustering algorithm based on the particle swarm optimization algorithm, which can reduce the network energy consumption and prolong the network lifetime. Wang *et al.* [32] presented a clustering mechanism based on the soft-defined network, in which the CH nodes are selected according to the energy threshold information broadcasted among the underwater nodes and then the nCH nodes connect with the CH node having the strongest signal strength. Wan *et al.* designed an energy efficient clustering routing algorithm in [33]. In this algorithm, they considered several factors such as the residual energy of each node and the transmission loss, and they suggested determining the effective communication range of each node by its residual energy and the distance to the base station. The studies mentioned above *only consider the single-hop transmission* between the CH node and the nCH node. In the multi-hop case, Ghoreyshi *et al.* [34] proposed a cluster-based mobile data gathering (CMDG) scheme, the clustering structure of the UWA-SN is built by limiting the transmission hops of each package and selecting the CH nodes according to the number of neighbor nodes of each underwater node. The experimental result demonstrated that, compare with the autonomous underwater vehicle (AUV) aided energy efficient routing protocol (AEERP) algorithm [35] and AUV-visits-path node (AUV\_PN) algorithm [36], the proposed scheme achieves a better communication performance and lower energy consumption. It is worth mentioning that none of the above studies considered *the cooperative technology* into the UWA-SN.

Therefore, motivated by [34], we proposed an energy optimization clustering scheme algorithm (EOCA) for the multi-hop UWA-CSN in this paper. We improve the original scheme by adding the reference factors such as the residual energy and the distance to the sink node for each underwater sensor node in the CH node selection. Moreover, we design an energy optimization mechanism for each underwater sensor node to set a proper maximum effective communication range. The target is that the energy consumption optimization is realized for the multi-hop UWA-CSN while the communication performance is guaranteed, so as to extend the life time of the multi-hop UWA-CSN.

### III. DESCRIPTION OF RELATED MODELS

#### A. THE MODEL OF MULTI-HOP UNDERWATER ACOUSTIC COOPERATIVE SENSOR NETWORKS

In this section, we will describe the model of the involved multi-hop UWA-CSN. In this paper, we mainly study the multi-hop UWA-CSN deployed in the shallow sea as Fig. 1



**FIGURE 1.** The model of the multi-hop UWA-CSN for the proposed EOCA clustering scheme.

shows, where there are a lot of underwater sensor nodes deployed to monitor the underwater environment and the activities of the marine life. The AUV is utilized to assist the communication between each underwater sensor node and the sink node. From Fig. 1 we can also find that, the multi-hop UWA-CSN has the clustering structure. The underwater sensor nodes in yellow represent the CH nodes, and the other nCH nodes will send their data to the corresponding CH nodes by directly transmitting or cooperative transmitting. For example,  $S_{10}$  sends data to  $S_4$  directly, and  $S_{11}$  sends data to  $S_4$  with the help of  $S_{12}$  by cooperative transmission as shown in Fig. 1. The details of cooperative transmission model for “ $S_{11}$ - $S_4$ - $S_{12}$ ” group can be found in our previous work [37]. After that, in order to collect the data of all underwater nodes, the AUV doesn’t have to communicate with all nodes but only needs to communicate with the CH nodes. In this way, the system communication traffic can be reduced.

In this research, we assume the AUV in the multi-hop UWA-CSN can always collect the data of each CH node correctly as long as the AUV can be close enough to the CH node due to the powerful energy supply of AUV. The optimal design of AUV data collection path among the CH nodes is beyond the scope of this paper.

**B. THE MODEL OF UNDERWATER ACOUSTIC CHANNELS**

As the application scenario we considered is in the shallow sea, according to [38], the transmission loss of the underwater acoustic signal can be expressed as:

$$A(l, f) = A_0 l^\kappa [\alpha(f)]^l \tag{1}$$

where  $l$  represents the transmission range in km,  $f$  represents the signal frequency in kHz, while  $A_0$  is the normalized coefficient,  $\kappa$  is the spreading factor, and  $\alpha(f)$  represents the absorption coefficient.

And (1) can be written into logarithmic form, which can be expressed as:

$$TL = 10 \log [A(l, f)/A_0] = \kappa \cdot 10 \log l + l \cdot 10 \log \alpha(f) \tag{2}$$

where the first term on the right side of (2) represents the spreading loss and the second one means the absorption loss.

In the field of underwater acoustic communications, we often use the Thorps formula to formulate  $\alpha(f)$  in (2), which gives [39]:

$$10 \log \alpha(f) = 0.11 \frac{f^2}{1 + f^2} + 44 \frac{f^2}{4100 + f^2} + 2.75 \times 10^{-4} f^2 + 0.003 \tag{3}$$

where  $10 \log \alpha(f)$  means the absorption coefficient in logarithmic form, and the unit is dB per km.

What’s more, the underwater ambient noise is also an important factor which affects the communication performance. The underwater ambient noise is influenced by various factors, such as the sea disturbance, the ship activities, the waves and water temperature. Conventionally, the underwater ambient noise can be expressed as [40]:

$$10 \log N_t(f) = 17 - 30 \log f \tag{4}$$

$$10 \log N_s(f) = 40 + 20(s - 0.5) + 26 \log f - 60 \log(f + 0.03) \tag{5}$$

$$10 \log N_\omega(f) = 50 + 7.5\sqrt{\omega} + 20 \log f - 40 \log(f + 0.4) \tag{6}$$

$$10 \log N_{th}(f) = -15 + 20 \log f \tag{7}$$

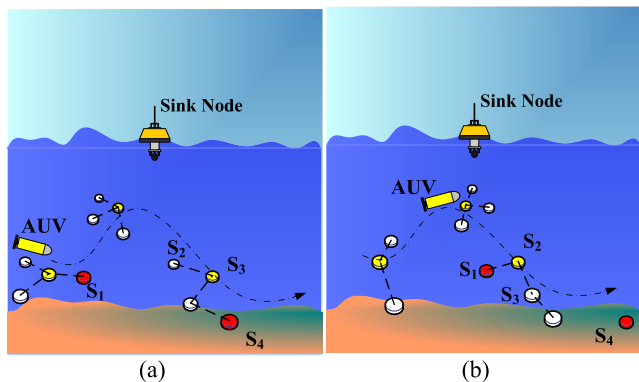
where  $s$  represents the shipping density,  $\omega$  is the wind speed in meter per second. These four equations (4) to (7) correspond to the calculation of the four sources (seismic movement, shipping activity, waves, and molecular agitation) of the underwater ambient noise mentioned above respectively. Then combine the above noise terms, the final aggregate underwater ambient noise can be expressed as:

$$NL = 10 \log (N_t(f) + N_s(f) + N_\omega(f) + N_{th}(f)) \tag{8}$$

**C. THE DRIFTED MODEL OF UNDERWATER SENSOR NODES**

Since the dynamics in the form such as currents are significant in real ocean environments, most likely the underwater sensor nodes will not always keep stationary, and their positions will change with the ocean currents as Fig. 2 shows. The initial clustering structure of the multi-hop UWA-CSN is drawn in Fig. 2 (a), the yellow underwater sensor nodes are the CH nodes and the other nodes are the nCH nodes. Then as the underwater sensor nodes drift with the ocean current, the distances between the underwater sensor nodes will change as Fig. 2 (b) shows. It can be found that node  $S_1$  has been changed to belong to another cluster, and node  $S_4$  becomes an isolated node because it is far from other underwater sensor nodes at this moment. Moreover, due to the changes of the residual energy and the distance to the





**FIGURE 2.** The schematic diagram of the network clustering structure affected by water current: (a) Before the underwater sensor nodes drifting; (b) After the underwater sensor nodes drifting.

sink node for each underwater sensor node, the selection of the CH nodes should be changed as well. In Fig. 2 (b), node  $S_2$  replaces the original CH node  $S_3$  to be the new CH node, while the node  $S_3$  becomes the nCH node at this moment.

At present, most of studies on the multi-hop UWA-CSN assume the positions of the underwater sensor nodes are fixed. However, it is inevitable that the mobility of the underwater sensor node caused by the ocean currents has a significant impact on the routing and clustering algorithms for the multi-hop UWA-CSN. Hence it is one of the important factors on the system communication performance. Motivated by this fact, the mobility of the underwater sensor nodes is considered in this paper.

In order to properly simulate the ocean currents in actual situation, we introduce a meandering current mobility model (MCM) in [41]. This model is designated for a typical large scale offshore shallow sea, which is similar with our application scenario. The trajectory of each underwater sensor node can be obtained by this MCM model, which mainly uses a flow function  $\psi$  to calculate the motion of water. Establishing a rectangular coordinate on the surface of sea and assuming the location of an underwater sensor node is  $(x, y)$ , then we can get:

$$\dot{x} = -\frac{\partial \psi(x, y, t)}{\partial y} \tag{9}$$

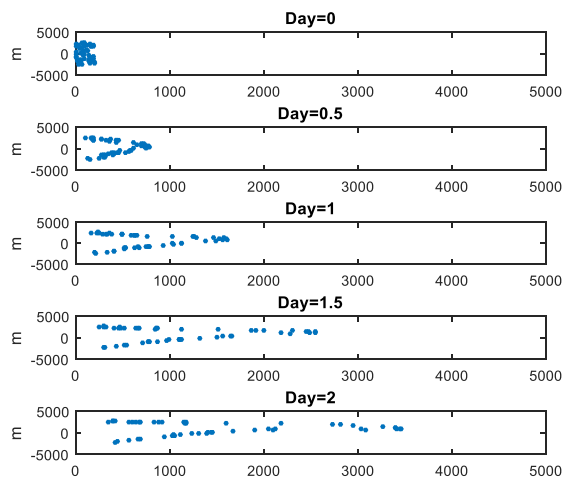
$$\dot{y} = -\frac{\partial \psi(x, y, t)}{\partial x} \tag{10}$$

where  $\dot{x}$  and  $\dot{y}$  respectively represent the distance the underwater sensor node moves along the X-axis and Y-axis at  $t$  moment, and the unit is km. The flow function  $\psi$  can be expressed as:

$$\psi(x, y, t) = -\tanh \left[ \frac{y - B(t)\sin(k(x - ct))}{\sqrt{1 + k^2 B^2(t)\cos^2(k(x - ct))}} \right] \tag{11}$$

where  $c$  represents the phase velocity,  $k$  represents the wave number.  $B(t)$  means the amplitude function of the meander, which is expressed as follow:

$$B(t) = B_0 + \varepsilon \cos(\zeta t) \tag{12}$$



**FIGURE 3.** The changes of positions with time for the underwater sensor nodes.

**TABLE 1.** The parameters setting of the MCM model.

Parameter	Value
$B_0$	1.2 km
$\varepsilon$	0.3
$\zeta$	0.4
$c$	0.12
$k$	$2\pi/7.5$

where  $B_0$  is the average width of the meander in km,  $\varepsilon$  is the amplitude in km, and  $\zeta$  is the frequency.

By using the above MCM model, we can calculate the moving track of each underwater sensor node. In Fig. 3, we demonstrate the changing process of the positions of 50 underwater sensor nodes over time by using the MCM model, where the related parameters setting of the MCM model is listed in Table 1.

From Fig. 3 we can see that as the initial position of each underwater sensor node is different, the moving speed of each node is different, the overall location distribution of underwater sensor nodes become gradually dispersed over time. However, we can find that all the underwater sensor nodes are almost moving along the X-axis, and there exists a phenomenon that some underwater sensor nodes are close to each other. This provides the possibility for us to build the clustering structure for the multi-hop UWA-CSN. Thus, in the case of the underwater sensor node moving by the ocean currents, we can still use the clustering technology to optimize the energy consumption for the multi-hop UWA-CSN.

#### IV. THE PROPOSED ENERGY OPTIMIZATION CLUSTERING SCHEME

##### A. THE PROPOSED ENERGY OPTIMIZATION CLUSTERING ALGORITHM

For the multi-hop UWA-CSN model mentioned in Section III, we propose an improved distributed scheme, named as EOCA

based on the CMDG algorithm introduced in [34]. In the proposed EOCA, the clustering structure of the multi-hop UWA-CSN is built in a decentralized way by which each underwater sensor node only needs to communicate with neighbor nodes. This avoids the large amount of global update information produced by the central controller, which will cost much energy resource for data transmission. In the distributed clustering approach, we can also reduce the complex situation brought by the data transmission collision and long delay in the network. More importantly, it is not necessary for the distributed clustering approach to obtain the exact locations of each underwater sensor nodes but just need the relative locations of them, which avoids the localization problem for each underwater sensor node in a centralized clustering approach.

The CH node selection is one of the critical processes for the clustering algorithms. The design of the CH node selection will affect the system communication performance, the load of each underwater sensor node, and even the stability of the network topology. In the clustering algorithm, each underwater sensor node firstly counts the number of neighboring nodes within  $d$  transmitting hops, which is called the potential number of nCH nodes based on  $d$ -hop for each underwater sensor node. Then the node with maximum potential number of nCH nodes based on  $d$ -hop is selected as the CH node in each locality. It means that if an underwater sensor node can connect with more neighboring nodes within its effective communication range, it is more likely to become the CH node. Assume the number of underwater sensor nodes is  $N$ , and one of them can connect with  $n_i$  ( $i = 1, 2, \dots, N$ ) neighbor nodes within its effective communication range, then the covering ratio  $\rho_i$  of this underwater sensor node can be calculated as:

$$\rho_i = \frac{n_i}{N} \quad (13)$$

According to (13), the larger the covering ratio is, the higher the probability of becoming the CH node for the underwater sensor node. However, the disadvantage of the CMDG is that it only considers the number of neighbor nodes, and the underwater sensor node with largest covering ratio will always be selected as the CH node. However, the CH node needs to consume more energy due to the data aggregating and relaying operations, which leads to the prematurely die of the underwater sensor node with largest covering ratio, and then causes the energy hole problem in the multi-hop UWA-CSN. To solve the above problem, we improve the CH node selection process and propose the EOCA algorithm. The detailed procedure of the EOCA is described in Algorithm 1.

At first, in the initial phase, we set a uniform maximum communication hops  $d$  for each underwater sensor node, and each underwater sensor node needs to obtain the related information from the neighboring nodes within  $d$  hops, including the hops and distances from each neighboring node to itself. The nCH nodes will select the CH node with the minimum distance for clustering if there are more than two CH nodes

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**Algorithm 1** The Proposed EOCA Algorithm
 

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1  Input  $c, k, B_0, \varepsilon, \zeta$ , initial the MCM model
2  Input  $d, d_m, DP$ , initial each underwater sensor node
    $N_i (i = 1, 2, 3, \dots, N)$ 
3  while  $DP > 0$  do
4    The sink node broadcasts information  $Init\_msg$ 
5    for each  $N_i$  do
6      Calculate  $l_{i,0}$  with respect to  $T_{i,0}$ 
7      Get the  $d_{i,j}$  and  $l_{i,j}$  ( $i = 1, 2, 3, \dots$ , and  $i \neq j$ )
       from neighbor nodes
8      Calculate  $t_i$  according to equation (15)
9    end for
10   while  $t_i > 0$  do
11     Receive the CH node information  $CH\_msgs$ 
       and get the current hops  $d_i$ 
12     if  $d_i < d$  then
13       Forward the  $CH\_msgs$ 
14     end if
15   end while
16   for each  $N_i$  do
17     if never receive any  $CH\_msgs$  then
18       Become a CH node and broadcast
       information  $CH\_info$ 
19     else
20       Become a nCH node and receive the
        $CH\_info$  from CH nodes directly or from the
       cooperative node
21       Send join information  $join\_msg$  to the
       closest CH node based on  $d_{i,j}$  and  $l_{i,j}$  directly or to
       the cooperative node
22     end if
23   end for

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with the same hops. What's more, each underwater sensor node has a unique ID number.

Next in the broadcasting phase, the sink node will broadcast a short package to each underwater sensor node, which contains the transmitting time. It is ensured that this package can be successfully received by all the underwater sensor nodes. Hence, each of them can obtain its distance to the sink node by calculating the transmission delay and using the following equation:

$$l_{i,0} = vT_{i,0} \quad (14)$$

where  $l_{i,0}$  represents transmission distance between the  $i$ -th underwater sensor node  $S_i$  and the sink node in km,  $v$  is the underwater acoustic speed in km per second and  $T_{i,0}$  represents the transmission delay between the node  $S_i$  and the sink node in second.

Then in the CH node selection phase, each underwater sensor node will compete with their neighboring nodes for being the CH node. In order to realize the load balance and energy optimization for the multi-hop UWA-CSN, besides the potential number of nCH nodes based on  $d$ -hop, we further consider the residual energy and the transmission

distance to the sink node of each underwater sensor node. Assume the residual energy of each underwater sensor node is  $R_i$  ( $i = 1, 2, 3, \dots, N$ ) and the unit is  $J$ , and the transmission distance between each of them and the sink is  $l_{i,0}$  ( $i = 1, 2, 3, \dots, N$ ) and the unit is km, then each underwater sensor node computes its delay time  $t_i$  ( $i = 1, 2, 3, \dots, N$ ) as the following:

$$t_i = \frac{\eta}{R_i} + \beta l_{i,0} + \gamma[(d_m - m_i)(DP/d_m)] \pm \lambda \quad (15)$$

where  $d_m$  represents the uniform maximum potential number of nCH nodes based on  $d$ -hop for each underwater sensor node,  $m_i$  ( $i = 1, 2, 3, \dots$ ) is the actual potential number of nCH nodes based on  $d$ -hop value of each underwater sensor node,  $DP$  is the clustering period in hour,  $\lambda$  represents a random time interval in second, which is utilized to differentiate the underwater sensor nodes with the same  $R_i$ ,  $l_{i,0}$  and  $m_i$ , while  $\eta$ ,  $\beta$  and  $\gamma$  respectively represents the weight of each term, and  $\eta + \beta + \gamma = 1$ .

From (15), we can observe that if an underwater sensor node  $i$  has larger  $R_i$ , smaller  $l_{i,0}$  and larger  $m_i$ , it would have a shorter delay time. Hence, the priority of the underwater sensor node being selected as the CH node is negatively correlated with  $t_i$ .

Before the delay timer is over, an underwater sensor node can continuously receive and store the broadcast information from its neighboring nodes, including their actual potential number of nCH nodes based on  $d$ -hop values, ID numbers and the initial transmitting times of the information. If the number of hops  $d_i$  from an underwater sensor node  $S_i$  to the neighbor node  $S_n$  with more potential of nCH nodes is less than the maximum communication hops, the node  $S_i$  will forward the broadcast information of the node  $S_n$ . Moreover, the node  $S_i$  would become *the cooperative node* to help other nCH nodes to communicate with the CH node in the same cluster.

If an underwater sensor node doesn't receive any broadcast information before its delay timer is over, it would become the CH node and inform the neighbor nodes while other nodes would become the nCH nodes and will receive and store the information from the CH nodes. Furthermore, the nCH nodes will decide whether to forward these CH nodes information or not based on its own potential number of nCH nodes based on  $d$ -hop. The nCH node will compare the  $d$ -hop of the CH node with its local  $d$ -hop, and then if the  $d$ -hop of the CH node is larger than the local  $d$ -hop in the nCH node, it will forward the CH node information.

Finally, in the clustering phase, according to the information collected from the CH nodes, the nCH nodes choose to join the CH node closest to each of them by sending the join information directly or with the help of the closest cooperative node indirectly. In this way, the clustering structure of the multi-hop UWA-CSN will be built. All the above phases form a completed clustering period.

## B. THE ENERGY OPTIMIZATION MECHANISM DESIGN FOR THE UNDERWATER SENSOR NODES

Currently in most of the related studies, the effective communication range of each underwater sensor node is set to a constant value and will not change during the running time. This assumption is helpful in the early time when all the underwater sensor nodes have sufficient energy and will perform the best transmission for the multi-hop UWA-CSN. However, as the system runs, some underwater sensor nodes will reach a low energy level because of the continuous energy consumption. In this situation, if the underwater sensor node with less energy still maintains a large effective communication range, it would prematurely die which will lead to the energy hole problem for the multi-hop UWA-CSN. In fact, it is difficult for an underwater sensor node to maintain a constant effective communication range when its residual energy is lower than a certain value.

Due to the above concerns, we design an energy optimization mechanism for the underwater sensor node in this paper. The idea of the proposed mechanism is to build a proper re-MECCR function to implement a unified control for the MECCR of each underwater sensor node. On one hand, the underwater sensor node will maintain a large effective communication range when its residual energy is sufficient. On the other hand, the underwater sensor node will adaptively decrease its MECCR when its own residual energy is lower than a threshold and becomes less and less, which is helpful to prolong the life time of the underwater sensor nodes.

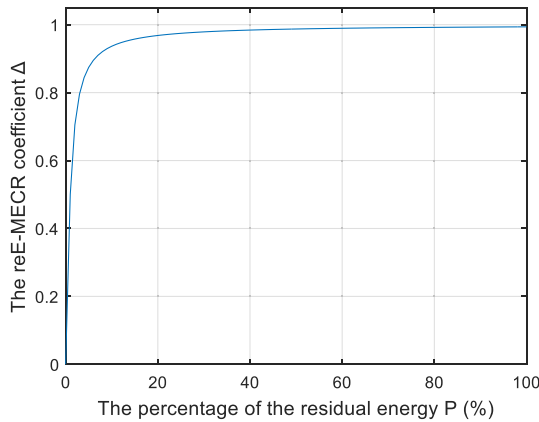
According to the above idea, we introduce the arctangent function to build the re-MECCR function. The details about this function are described as follows. If the initial MECCR of an underwater sensor node is  $R_m$ , the initial energy of it is  $E_0$ , and at one moment, its residual energy becomes to be  $E$ , then the re-MECCR of this underwater sensor node can be calculated by:

$$R = \frac{2R_m}{\pi} \arctan\left(\frac{E}{E_0} \times 100\%\right) \quad (16)$$

The above function represents the relationship between the MECCR and the percentage of the residual energy in the initial energy. Assume the percentage is  $P = E/E_0$ , and then the relative coefficient of the re-MECCR can be defined as:

$$\Delta = \frac{R}{R_m} = \frac{2}{\pi} \arctan(P) \quad (17)$$

And the curve of the (17) is plotted in Fig. 4, we can see that the coefficient converges to 1 when the percentage is larger than 20%. On the contrary, when the percentage is lower than 20%, the re-MECCR begins to sharply drop and will become 0 when the percentage is 0, i.e. the underwater sensor node would lose the transmission capability when its energy is exhausted. Through using the proposed re-MECCR function, which is more practical in the real situation, we can achieve the goal of adaptively adjusting the MECCR of the underwater sensor node according to its residual energy. When combining the proposed EOCA algorithm with the proposed energy



**FIGURE 4.** The curve of the maximum effective communication range coefficient versus the percentage of the residual energy for the underwater sensor node.

optimization mechanism, the underwater sensor nodes will calculate their MECRs before each clustering period. As a result, the number of neighboring nodes of each underwater sensor nodes may be changed in different clustering periods because of the change of the MECR.

Therefore, in our proposed energy optimization clustering scheme, we will combine the proposed EOCA scheme with the reE-MECR energy optimization mechanism.

## V. SIMULATION

### A. THE RELATED PARAMETERS SETTING

The simulation is carried out based on the MATLAB software platform, the computer operating system is Windows 7 (64-bit), the CPU is i3-4170, and the memory is 8 GB.

Similar to [34], the parameters settings are listed in Table 1 and Table 2. The size of the multi-hop UWA-CSN is  $10000 \times 10000 \text{ m}^2$ , the number of the underwater sensor nodes is set to be 50, and these nodes are randomly and uniformly deployed at 20 meters depth from ocean surface. The initial energy of each underwater node is 40000 J. Moreover, we assume the energy of the sink node can be charged by solar or wind energy, so its energy is always abundant.

Especially, we set the maximum wind speed to 15 m/s, the maximum ship density is set to 1, and these two parameters will change over simulation, i.e., their maximum values are multiplied by a random number evenly distributed within the interval (0,1). In this way, the uncertainty of the underwater acoustic communication environment is simulated. In the simulation, we assume each underwater sensor node transmit 5 s length signal in each hour. Then we perform a total of 200 times Monte Carlo simulations.

From the study in [34], we know that when the edge length of the network coverage area is larger than 1500 m, the CMDG is much better than AUV\_PN and AEERP schemes. With the increasing of edge length, the performance advantage is even more obvious. In this paper, the edge length of the coverage area is from 6000 m to 15000 m (generally 10000 m), which is much larger than 1500 m. Therefore, for

**TABLE 2.** The related parameters settings.

Parameter	Value
Network coverage area	$10000 \times 10000 \text{ m}^2$
Number of underwater sensor nodes	50
Deployed depth	20 m
Initial energy of each node	40000 J
Power in idle mode	0.008 W
Transmitting power	50 W
Receiving power	0.158 W
Initial MECR	2000 m
Signal frequency	12 kHz
Modulation mode	OFDM
Maximum number of retransmissions	1
Maximum number of hops in each cluster	2
Maximum potential number of nCH nodes based on $d$ -hop in each cluster	9
Maximum wind speed	15 m/s
Maximum ship density	1

the sake of simplicity in this manuscript, we only present the comparison results between our proposed scheme and the CMDG scheme which has the best performance at present.

Based on the above general parameter setting, Fig. 5 and Fig. 6 present the network clustering results for the CMDG scheme and the proposed EOCA scheme respectively. We can observe that the proposed EOCA scheme needs 6 CH nodes only, while the existing CMDG scheme needs 9 CH nodes. This is because in the proposed EOCA scheme, when selecting the CH nodes, we not only consider the number of neighboring nodes of each underwater sensor node, but also their distances to the sink node and their residual energy. The less CH nodes selected means the higher efficiency for the AUV to finish the data collection, as the AUV only needs to collect data from the CH nodes for the sink node in this network.

### B. THE PERFORMANCE COMPARISON BETWEEN THE PROPOSED SCHEME AND THE EXISTING SCHEME

In this section, we give out the dynamics of the system performance parameters with the running time, and make a comparison between the proposed EOCA scheme and the existing CMDG scheme. Fig. 7 shows the system residual energy performance with the running time. We can observe that the energy consumption speeds of the two schemes are the same at the beginning, but the energy consumption speed of EOCA scheme is gradually lower than that of CMDG scheme. This is because the MECR of the underwater sensor node in the EOCA scheme is dynamic, while that in the CMDG is set as a fixed value. It means the energy consumption of the underwater sensor nodes in EOCA scheme will be more



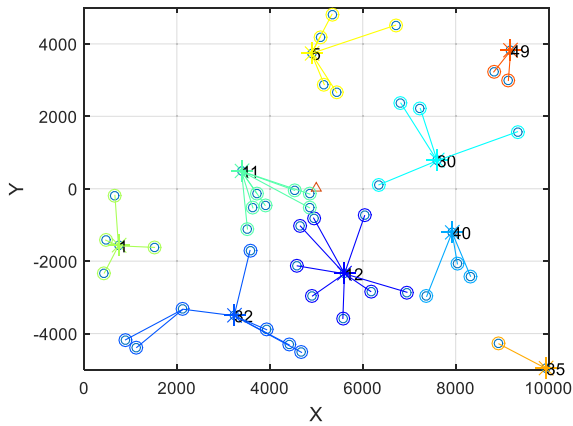


FIGURE 5. The network clustering result of the CMDG scheme.

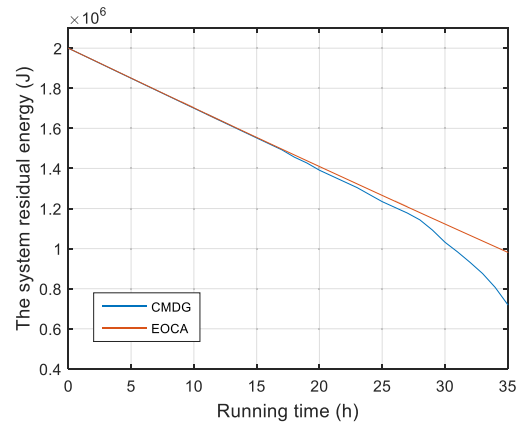


FIGURE 7. The system residual energy changes with the running time.

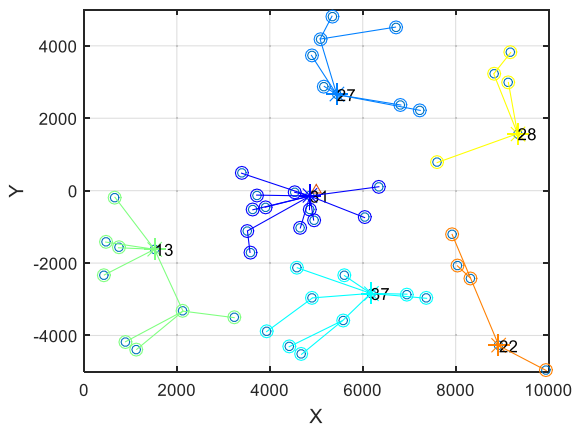


FIGURE 6. The network clustering result of the proposed EOCA scheme.

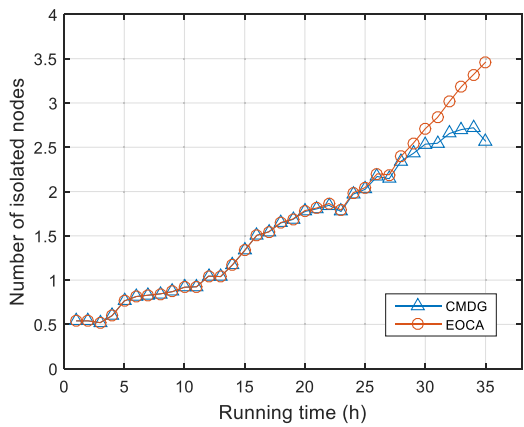


FIGURE 8. The number of isolated nodes changes with the running time.

efficient than that in CMDG scheme. As it only considers the potential number of  $n$ CH nodes based on  $d$ -hop in the CH node selection phase for the CMDG scheme, the underwater sensor node with the larger potential number of  $n$ CH nodes based on  $d$ -hop will be often selected as the CH node, which leads to more energy consumption than other nodes. This is the energy hole problem in the multi-hop UWA-CSN. Since the proposed EOCA scheme can effectively avoid the energy hole problem, the residual energy of the proposed EOCA scheme is gradually more than that in the existing CMDG scheme with the running time.

Fig. 8 shows the dynamics of the number of isolated nodes with the running time. The isolated node is defined as the underwater sensor node that fails to cluster with other nodes in the network. This result indicates that as the time goes, the isolated nodes will both increase when using the two schemes but the increase is slight. Concerning that the underwater sensor node will move with the ocean current, it is reasonable for the above phenomena when some nodes are drifting to a far position to others. In the proposed EOCA scheme, due to the benefit of the proposed reE-MECCR scheme in the energy optimization mechanism for the underwater sensor nodes, the MECCR of each node will reduce as their resid-

ual energy decrease, which may increase the probability of creating an isolated node. However, this difference is not significant, which means the stable status of the multi-hop UWA-CSN structure are almost the same when using the two schemes.

In Fig. 9, the package delivery ratio result is plotted for the ocean current multi-hop UWA-CSN when using the two different schemes. The package delivery ratio is defined as the ratio of the packages successfully received by all underwater sensor nodes to the total transmitting packages. From Fig. 9, we can find that the package delivery ratio performance of the EOCA scheme is as good as that of the CMDG scheme and the package delivery ratios reach at about 90% for both two schemes. Hence by adopting the EOCA scheme, the multi-hop UWA-CSN can achieve a good communication performance.

The network life time result of the multi-hop UWA-CSN is drawn in Fig. 10 for the two schemes. We here define the time when the first energy exhausted underwater sensor node arises as the network life time of the multi-hop UWA-CSN.

In Fig. 10, the triangular marker represents the network life time of the multi-hop UWA-CSN when adopting EOCA

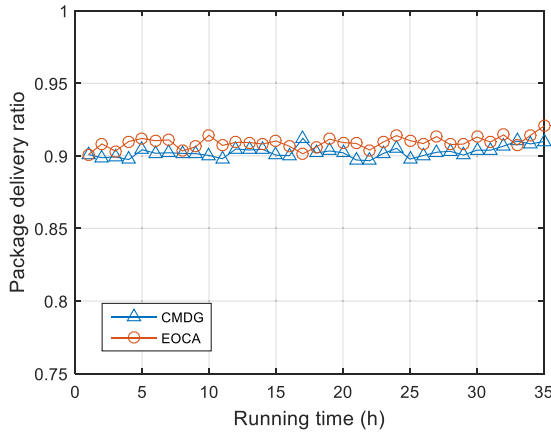


FIGURE 9. The system package delivery ratio changes with the running time.

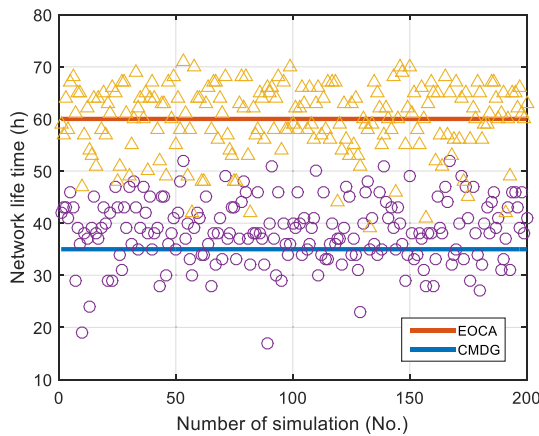


FIGURE 10. The statistics of the UWA-CSN life time for each simulation.

scheme in each simulation round, and the red line is the average value of them. While the circled marker represents the corresponding result when adopting CMDG scheme, and the blue line is the average value of them. It is evident that the network life time of using the proposed EOCA scheme is longer than the existing CMDG case, which demonstrates the effectiveness of the proposed EOCA scheme in prolonging the network life time for the multi-hop UWA-CSN.

**C. THE INFLUENCE OF THE NETWORK COVERAGE AREA FOR THE PROPOSED SCHEME**

In this section, we study the influence of the network coverage area for the proposed EOCA scheme. In this simulation, the network coverage area of the multi-hop UWA-CSN is set from  $6000 \times 6000 \text{ m}^2$  to  $15000 \times 15000 \text{ m}^2$ , the number of the underwater sensor nodes is set to be 90, and the other parameters are the same as the values mentioned in Section. V.A. Firstly, we give out the related performance results varying with the network coverage area without considering the mobility of the underwater sensor nodes.

In Fig. 11, we give the number of the CH nodes result of the multi-hop UWA-CSN when using different clustering

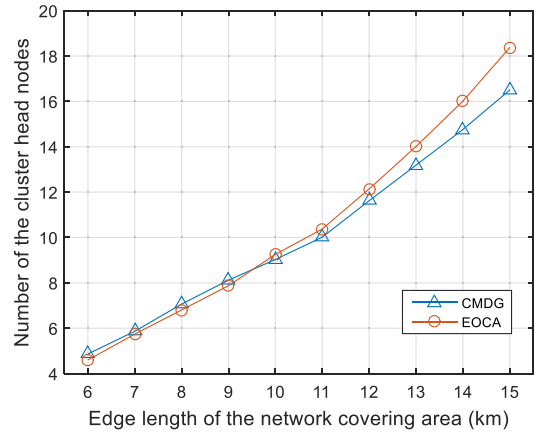


FIGURE 11. The number of the cluster head nodes changes with the network coverage area.

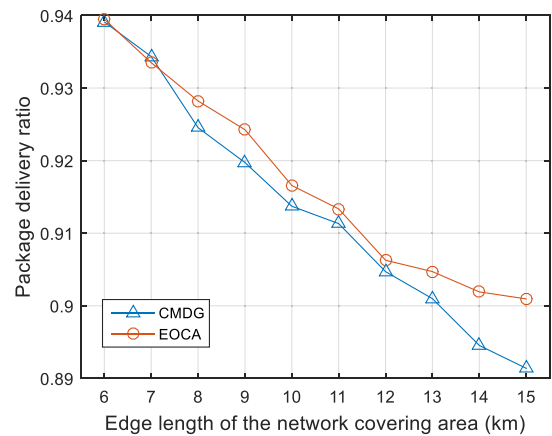


FIGURE 12. The system package delivery ratio changes with the network coverage area.

schemes. The X-axis in Fig. 11 represents the edge length of the network coverage area. We can see that the number of the CH nodes is gradually arising as the network coverage area of the multi-hop UWA-CSN increases for both of the two clustering schemes. When the network coverage area is smaller than  $10000 \times 10000 \text{ m}^2$ , the increasing trends of the number of the CH nodes are consistent for the two different clustering schemes. However, when the network coverage area is larger than  $10000 \times 10000 \text{ m}^2$ , the increasing trend in the EOCA scheme becomes faster, which means it will need larger number of CH nodes. We can find that as the increasing of the network coverage area, the structure of the multi-hop UWA-CSN will tend to discretize no matter when using the EOCA scheme or the CMDG scheme. This is caused by the decrease of the density of the underwater sensor nodes, i.e., the distances between each node will increase correspondingly.

The influence of the network coverage area on the package delivery ratio is drawn in Fig. 12. For the two different clustering schemes, the package delivery ratio will decrease as the network coverage area arises. Yet when using the EOCA scheme, the package delivery ratio of the multi-hop

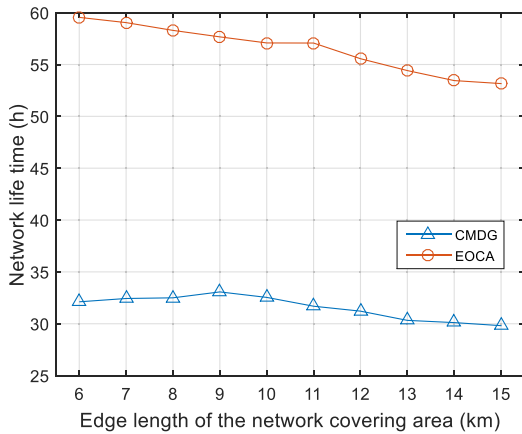


FIGURE 13. The multi-hop UWA-CSN life time changes with the network coverage area.

UWA-CSN outperforms the case of the CMDG scheme. Moreover, when the network coverage area is larger than  $12000 \times 12000 \text{ m}^2$ , the performance decreasing trend of the EOCA scheme begins to be slow; While in the CMDG scheme, it almost keeps a constant decreasing trend. This means the proposed EOCA scheme can obtain a higher package delivery ratio performance as the network coverage area arises compared with the existing CMDG scheme. This is because in the proposed EOCA scheme, we consider more factors when selecting the CH nodes, so much more suitable CH nodes are selected to guarantee a better package delivery ratio.

Next, combined with the mobility of the underwater sensor node, we present the life time result of the multi-hop UWA-CSN in Fig. 13 for the two different clustering schemes. From Fig. 13, it can be observed that when using the two different schemes, the life times of the multi-hop UWA-CSN will both decrease as the network coverage area increases, because of the increase of the energy consumption for each package transmission. Furthermore, it can be observed that the life time performance of the EOCA scheme is much better than that of the CMDG scheme. This is because that the energy consumption speed can be controlled properly in the EOCA scheme through the proposed reE-MECC energy optimization mechanism for each underwater sensor node, which is consistent with the results in Fig. 10.

#### D. THE INFLUENCE OF THE NUMBER OF UNDERWATER SENSOR NODES FOR THE PROPOSED SCHEME

In this section, we mainly analyze the influence of the number of underwater sensor nodes on the proposed EOCA scheme. We set the number of the underwater sensor nodes from 30 to 200, and the other parameters are the same as the values mentioned in Section V.A. Similarly, we firstly ignore the mobility of the underwater sensor node as the previous section did and give out the relevant results.

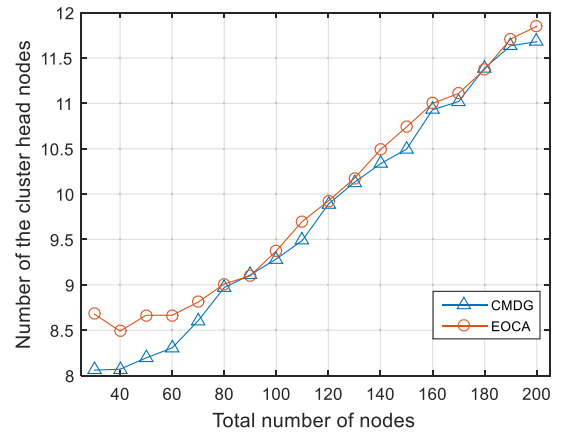


FIGURE 14. The number of the cluster head nodes changes with the total number of the underwater sensor nodes.

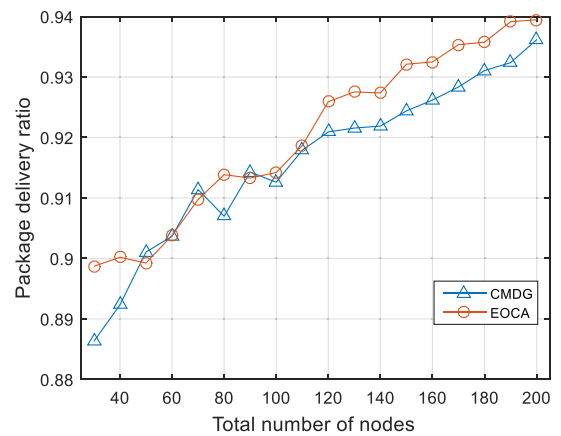
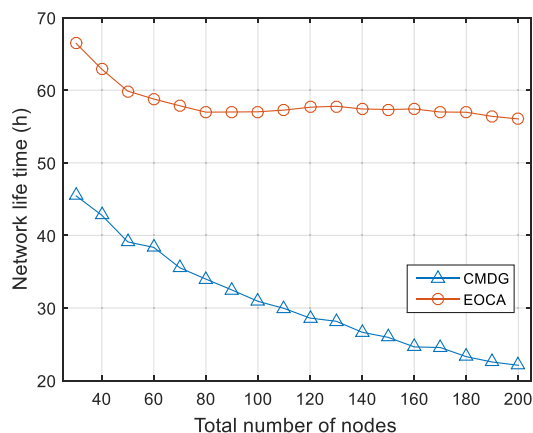


FIGURE 15. The package delivery ratio changes with the total number of the underwater sensor nodes.

The influence of the number of the underwater sensor nodes on the number of the CH nodes is shown in Fig. 14. Fig. 14 indicates that the number of the CH nodes is always increasing as the number of the underwater sensor nodes increases, whether using the proposed EOCA scheme or the CMDG scheme, and the increasing trend is similar to the CMDG case for the proposed EOCA scheme.

The influence of the number of the underwater sensor nodes on the package delivery ratio of the multi-hop UWA-CSN is plotted in Fig. 15. We can clearly see that when the network coverage area remains unchanged, the package delivery ratio of the multi-hop UWA-CSN would gradually increasing as the number of the underwater sensor nodes increases for both two clustering schemes. Besides, in the case where the number of the underwater sensor nodes is larger than 110, the multi-hop UWA-CSN can achieve a higher package delivery ratio when using the proposed EOCA scheme. Hence it is confirmed that the proposed EOCA scheme can provides a better package delivery ratio performance for the multi-hop UWA-CSN, and this performance would improve as the number of the underwater sensor nodes increases.



**FIGURE 16.** The multi-hop UWA-CSN life time changes with the total number of the underwater sensor nodes.

Next, combined with the mobility of the underwater sensor nodes, we show the influence of the number of the underwater sensor nodes on the life time of the multi-hop UWA-CSN in Fig. 16. It is evident that the multi-hop UWA-CSN can work in a longer network life time when using the proposed EOCA scheme. Moreover, with the increase of the number of the underwater sensor nodes, the network life time of the multi-hop UWA-CSN will drop gradually when using the CMDG scheme; while the network life time in the proposed EOCA scheme would stay in a high level.

In short, all the above simulation results have proved that the proposed EOCA scheme can achieve the goal of effectively optimizing the system energy as well as providing a good communication performance for the multi-hop UWA-CSN. Furthermore, we can observe that the proposed EOCA scheme has an excellent scalability which is feasible and suitable for the different sizes and different densities of the multi-hop UWA-CSN.

## VI. CONCLUSION

In order to deal with the energy optimization problem, we propose an improved energy optimization clustering algorithm based on the CMDG scheme, named as the EOCA scheme, for the multi-hop UWA-CSN. The EOCA scheme considers multiple factors in the procedure of CH nodes selection, including the neighbor nodes number, residual energy and distance to the sink node for each underwater sensor node. Furthermore, we design a reE-MECCR energy optimization mechanism in the CH nodes selection, which utilizes the curve characteristic of the arctan function to construct the uniform relationship between the residual energies of each underwater sensor node. We also consider the mobility of the underwater sensor nodes by introducing the MCM model in the proposed energy optimization clustering scheme. As a consequence, the simulation results demonstrate that the system can effectively prolong the life time while achieving a high package delivery ratio, by using the proposed energy optimization clustering scheme for the multi-hop UWA-CSN.

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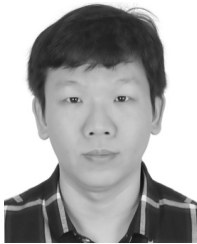
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