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RESEARCH

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An energy-balanced head nodes selection scheme for underwater mobile sensor networks

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Abstract

Underwater sensor networks system is a promising technology for smart ocean monitoring applications. To address the imbalance problem of network overhead and limited energy of underwater sensor nodes, this paper presents a CH–SH Selection and Sink Path-planning (CSSP) scheme to collect vast amount of data from heterogeneous sensor nodes. The scheme firstly establishes a three-layer network structure model for underwater mobile sensor networks (UMSN) based on multi-mode communication mechanism and provides energy-balanced head nodes (cluster head and sub-cluster head nodes) selection algorithm based on particle swarm iterative optimization. Then, the optimal global-path-plan of mobile sink is proposed to visit all the head nodes to collect data, reduce the multi-hop underwater acoustic transmission distance of relay nodes, and avoid the energy hole problem. Lastly, the upper-layer multi-hop network of UMSN is designed to remotely control local-path-plan over mobile sink, in order to implement joint planning of global and local paths of mobile sink. Simulation results verified that the proposed CSSP scheme outperformed 11%, 16% and 22% over three typical protocols in terms of nodes energy consumption, CSSP was 9%, 12% and 19% lower than three typical protocols in terms of SD of energy consumption, packet delivery ratio of CSSP was 8%, 10% and 12% higher than three typical protocols. The scheme could significantly balance energy and reduce packet loss rate.

Keywords: Underwater mobile sensor networks, Sub-cluster head, Head nodes selection, Global and local-path-plan, Energy balance

1 Introduction

Underwater environmental monitoring in the ocean has become part of economic development and border security construction in many countries. It is important to build dynamic three-dimensional ocean monitoring and responding system for environmental monitoring, and emergency rescue in maritime boundary areas [1]. The ocean contains massive amount of data and information, these data resources could be collected by different kinds of underwater sensor devices in smart ocean applications. The sensor devices are deployed in different areas to monitor various underwater environment parameters, such as underwater temperature, pressure, wave, nutrients, COD, dissolved oxygen, petroleum pollutants, PH, underwater video and images, as mentioned by Tie [2] and Asadi [3]. As deploying a large number of sensor devices in certain underwater

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areas is a challenge, an underwater wireless sensor network system is an appropriate technology to realize underwater monitoring, and this network is easy to deploy.

Underwater wireless sensor networks system is increasingly becoming powerful and low-cost technology for developing smart ocean application, such as underwater Internet of Things construction, Marine ranching monitoring, ocean ecological protection, and ocean disaster warning application [4]. In the underwater wireless sensor networks, distributed underwater sensor nodes can form a self-organizing network, sense and monitor underwater objects [2], and transmit sensing data to sink node by multi-hop wireless communication. Wireless communication includes underwater acoustic (UA) communication and radio frequency (RF) communication. Placing a large number of self-organized sensor nodes on the seabed (ocean bottom) can cover a large monitoring area, which is mentioned by Zhang [5], Saeed [6], and Luo [7]. This sensor networks system can be used to build marine monitoring network for Marine ranching, which can monitor ocean elements such as seawater temperature, salinity, depth, profile temperature salt, dissolved oxygen, chlorophyll, turbidity, and pH. By analyzing data, the monitoring ability and warning level of environmental emergencies such as enteromorpha, red tide, green tide, sea ice and oil spill can be improved. The underwater acoustic network system developed by Xiamen University [8] is a typical underwater sensor network, which can achieve 4.8 kbit/s data rate when the node's horizontal communication distance is 820 m.

Meanwhile, mobile sink (such as Automatic Underwater Vehicle, AUV) is a powerful solution to take advantage of short-range transmission [9, 10], for the mobile sink can effectively collect and transmit large amount of data [11]. It could move according to path-planning and collect data in sensing area and return to the shore-based base station to upload data efficiently, which is suggested by authors of [12]. The mobile sink-based underwater wireless sensor network could be an effective network to collect data and be improved to apply in the paperwork. Although the common path-planning method for mobile sink (AUV) is to traverse all the nodes in the network, it would augment total touring time and increase the operational cost of mobile sink. Therefore, how to design an optimal path-planning method for mobile sink and a network structure to satisfy the requirement of network energy balance should be discussed.

Besides it, diverse packets coexist under underwater wireless sensor network scenarios, so different delivery strategies are required to satisfy application demands. These packets include small amount of ocean monitoring packets (temperature, salinity and depth information and so on) and large amount of multimedia-based detection packets (video, images and so on). However, the limited bandwidth and high propagation delay of acoustic channels make it easier to satisfy large-distance monitoring packets demand, but pose great challenges to satisfy multimedia-based packets demand [13]. To provide a solution for multimedia-based data delivery, underwater RF communication could be used to collect large amount of data at high speed. This underwater RF channel communication can achieve 10 Mbps, but can only provide short-distance communication [14], which is suitable for short-distance data exchange between mobile sink and sensor nodes. Therefore, the design of multi-mode communication mechanism (combination of underwater acoustic (UA) and radio frequency (RF) communication) could balance the large data volume with high-speed transmission limitation.

Finally, when urgent events occur in area $\boldsymbol{A}$, mobile sink needs to stop its regular cruising and move to $\boldsymbol{A}$, focusing on gathering data in area $\boldsymbol{A}$. After dealing with these urgent events, the mobile sink would continue its cruising. In this situation, the problem of how to remotely control the moving path of mobile sink should also be addressed, in order to realize the remote control of base station over the mobile sink. The mobile sink-based underwater wireless sensor networks system is called underwater mobile sensor networks (UMSN) in this paper.

Generally speaking, there are three key issues to be solved: (1) The imbalance of network energy and overhead for UMSN needs to be solved. (2) How to balance the problem of large data transmission with data transmitting speed limitation. (3) The problem of remotely controlling the moving path of mobile sink should be considered.

Aiming at solving these data gathering and energy imbalance problems, the main contributions of this paper are as follows:

(1) The three-layer multi-hop network topology is proposed in the underwater mobile sensor networks (UMSN). The cluster heads (CH) would divide the cluster into several sub-clusters and select several nodes to be the sub-cluster head (SH) by particle swarm optimization algorithm (PSO), in order to collect data from inner-sub-cluster sensor nodes and reduce the multi-hop transmission distance of relay nodes. Then, the shortest moving path of mobile sink is planned.
(2) The PSO algorithm is provided to optimize the fitness function of head nodes selection. The particle swarm iterative optimization can quickly search for optimal CHs and SHs, and CH and SH can act as store points for the mobile sink to visit. This CH–SH Selection and Sink Path-planning (CSSP) scheme could balance network energy and avoid energy hole problems.
(3) The upper-layer multi-hop network is proposed to remotely control local-path-plan of mobile sink, implementing joint planning of global and local paths of mobile sink. The multi-mode communication (UA and RF) mechanism is also provided to save energy consumption of UMSN and solve the bottleneck problem of the underwater communication speed and distance conflict.
(4) Simulation results demonstrate that the proposed CSSP scheme can significantly balance energy and reduce packet loss rate. Compared with PNG, ACMC and AA-RP, the CSSP scheme outperforms 11%, 16% and 22% in terms of nodes energy consumption, SD of energy consumption of CSSP is reduced by 9%, 12% and 19%, packet delivery ratio of CSSP is increased by 8%, 10% and 12%.

The rest of this paper is organized as follows. Related work is shown in Sect. 2. Section 3 describes the UMSN model. Section 4 presents the CH–SH Selection and Sink Path-planning (CSSP) scheme in detail. Section 5 evaluates the performance of the protocol by comparing it with other similar protocols. Finally, the conclusion is presented in Sect. 6.

2 Related work

There are several papers focusing on mobile sink-based underwater wireless sensor networks (UMSN) recently, such as Basagni [15] and Ghoreyshi [16]. In article [17], a Greedy Heuristic protocol (GAAP) was presented for driving a mobile sink (AUV) to collect and deliver data with decaying value from nodes of UMSN. The aim was to find paths for the mobile sink that maximized the Value of Information (VoI) of the data delivered to the sink. This model considered realistic and desirable network sizes, data communication rates, distances and surfacing constraints. GAAP could find optimal paths and obtain VoI of delivered data, as the number of nodes increased. The authors of [18] proposed an AUV-aided acoustic communication protocol namely AA-RP, in which AUV collected data from sensor nodes and followed a dynamic path. Relying on the dynamic path of AUVs, the network topology was rebuilt, and sensor nodes can overcome energy hole problem. Although this is a common method for mobile sink (AUV) to traverse all the nodes in [17, 18], its long traveling time would cause failure in timely actions in emergency cases. This mobile sink path-planning method would also increase the total cruising time of mobile sink and its operating cost.

Some articles (such as Huang [19] and Qin [20]) have provided data collection schemes for UMSN based on cluster networking to solve this problem. The authors of [19] proposed an AUV-assisted data gathering scheme based on clustering and matrix completion (ACMC), which can realize the comprehensive optimization of energy and delay in the UMSN. A two-phase AUV trajectory optimization mechanism was proposed to effectively reduce the trajectory length of AUV and the workload of cluster heads. The extensive experiment validated effectiveness of the scheme. The authors in [20] introduced a cluster head dynamic conversion mechanism by considering energy load and node survival rate in their energy-aware clustering protocol for UMSN. In the AUV motion layer, they established a reliable AUV trajectory model to quantify the angle change during its operation. Meanwhile, far-sighted feature of MRP to path optimization was applied. Finally, simulation results validated the performance of designed algorithms. In articles [19, 20], if small number of CHs are evenly deployed in the network to collect and store data sensed by sensor nodes in the cluster, the trajectory length of the mobile sink path-plan can be reduced [21]. However, if mobile sink only traverses CHs among the clusters, mobile sink has to wait for all information to be retrieved from the nodes before moving to the CH. The multi-hop route in cluster would also consume much energy and increase link failure probability, so the sub-cluster head mechanism should be introduced into network to achieve energy balance.

For this reason, the authors of [22] proposed a mobile sink-based data gathering scheme by using a sub-cluster networking mechanism. The scheme allowed mobile sink to come by some selected path-nodes (PN) from each cluster to reduce the overall transmission power, and PN can be considered as sub-cluster head (SH). The CH nominated some PNs for each cluster to collect local data from the member nodes (MN) and reduced the impact of un-equal inter-nodal transmission distance. Mobile sink communicated with CH to identify PNs and visited the PNs to collect data from PNs. But this PN gathering protocol (PNG) did not consider that the sink should visit CH node, for the CH can also sense and store large amount of data. In addition, more influencing factors for selecting PN should be considered to improve this scheme. Thereby, an improved sub-cluster and cluster-based network could be a solution to address the network energy balance problem of underwater wireless sensor networks (UMSN).

3 UMSN network model

The UMSN network model contains three types of heterogeneous nodes: CH node, sensor node (including SH node), and mobile sink. The network is divided into several clusters, each cluster is divided into several sub-clusters. Each cluster contains one cluster head (CH), and each sub-cluster contains one sub-cluster head (SH), as shown in Fig. 1. In this section, the heterogeneous nodes model and energy consumption model are described in detail.

3.1 Heterogeneous nodes model in UMSN network

In the heterogeneous nodes model, the CH nodes are sparsely deployed on the seabed plane (ocean bottom). The CH can collect large amount of data (such as video and image multimedia data) from seabed environment, its UA and RF transmitters can transmit and receive UA and RF signals, respectively. CH also collects data from inner-cluster sensor nodes via multi-hop route. The large-capacity storage module of CH can store data, messages and commands. The CHs would send the stored data to the mobile sink using RF communication, when mobile sink moves nearby CH and visits CH. If one CH node is failed, the mobile sink would replace it with a new CH.

The SH node is selected from sensor nodes in each cluster, so its performance parameter is the same as sensor nodes. SH can collect large amount of data from surrounding inner-sub-cluster nodes. The SH also belongs to the CH and exchanges message and command with CH. If it is failed, another alternative SH would be selected from inner-sub-cluster sensor nodes, or the mobile sink would replace it with a new one. The SHs would wait for mobile sink to visit and upload stored data to mobile sink using RF communication. The upper-layer network of CHs and SHs is responsible for multi-hop uploading small amount of event messages to the base station. It would also broadcast local-path-plan commands from base station to each CH and SH.

The sensor nodes are densely deployed on the seabed plane. The sensor node only has acoustic transmitter module, small-capacity storage module can store data, and

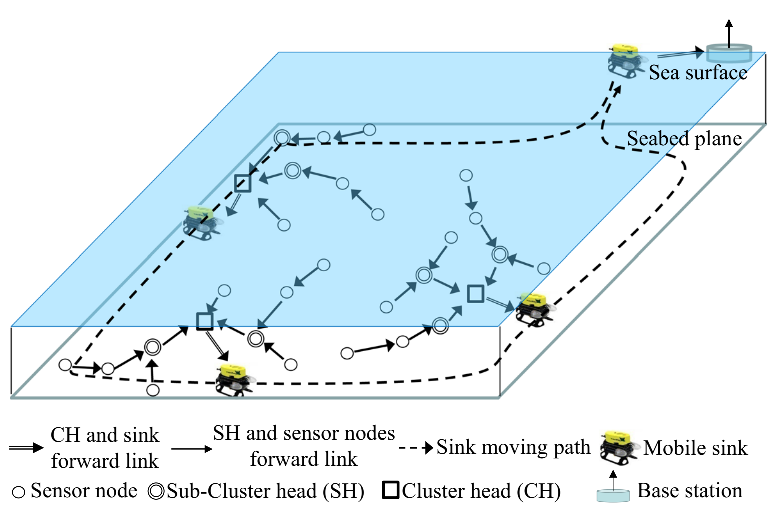


Fig. 1 Mobile sink moving path-plan diagram for the UMSN model

small-capacity battery can save device cost. The sensor nodes would forward large amount of data to their SH or CH via multi-hop route by underwater acoustic communication.

The mobile sink moves within the region covered by UMSN network and owns large storage space, short communication distance, and fast-moving speed. Its acoustic and RF transmitters can transmit and receive acoustic and RF data. Its robot arm can retrieve failed nodes and place alternative nodes, and its Doppler log meter can record the miles that the mobile sink has already sailed.

The mobile sink would visit each CH to receive large amount of data using RF communication, visit each SH to receive small amount of data, and control command messages by acoustic communication. Then, the mobile sink would move to the base station to upload data using RF communication and restart the round trip movement. By this means, the multi-mode communication mechanism (acoustic and RF communication) is formed and adopted.

To sum up, CH generates multimedia data itself and also collects data from inner-cluster sensor nodes via multi-hop route. Then, CH uploads data (including multimedia data) to mobile sink using RF. SH collects data from its inner-sub-cluster sensor nodes and uploads data to mobile sink using UA communication. CHs and SHs can also form the upper-layer network and only transmit event messages or commands among CHs, SHs and base station using UA communication. Mobile sink visits all the CHs and SHs to collect data, moves to the base station and uploads data to the base station. These heterogeneous nodes' data forwarding direction and nodes status transfer diagram are presented in Fig. 2. The notation of used symbols is in Table 1 at the end of the paper. The explanations of upper-layer and lower-layer networks are in Sects. 3.2.3 and 3.2.4.

Suppose there exist n $(0<n<N-1)$ sensor nodes, m $(0<m<N-1)$ CHs, k $(0<k<N-1)$ SHs, and *one* mobile sink in the UMSN model, and total nodes number is $N(v)=n+m+k$. v_j^i $(0<i<n)$ is the i-th sensor node in the j-th cluster, v_{CH}^j $(0<j<m)$ is the j-th CH node, $v_{\mathrm{SH}_l}^j$ $(0<l<k)$ is the l-th SH node of the j-th cluster, and v_{Sink} is the mobile sink. Sensor nodes in the cluster of v_{CH}^j forward their sensed data via multi-hopping path to the SH $v_{\mathrm{SH}_l}^j$ and CH v_{CH}^j. Then, v_{CH}^j and $v_{\mathrm{SH}_l}^j$ store packets and upload to v_{Sink} when v_{Sink} visits them in turn. The fundamental problem then becomes identifying the optimal SHs and CHs for the sink to visit, and planning optimal global moving path of mobile sink.

The network model is based on the following assumptions: (1) The sensor nodes, SHs and CHs are distributed on the seabed in the form of $2D$ plane. (2) Sensor nodes, SH and CH are static after being deployed, and mobile sink moves constantly with a relatively fixed underwater speed. (3) Data are sensed and forwarded from sensor nodes to their SHs and CHs via multi-hop route every *M minutes* interval.

3.2 Energy consumption model of UMSN network

A typical acoustic modem is used in underwater communications for packet transmission, as described in [23]. The passive sonar equation models the SNR in $dB\ re\ \mu\ Pa$ of an acoustic wave at a receiver.

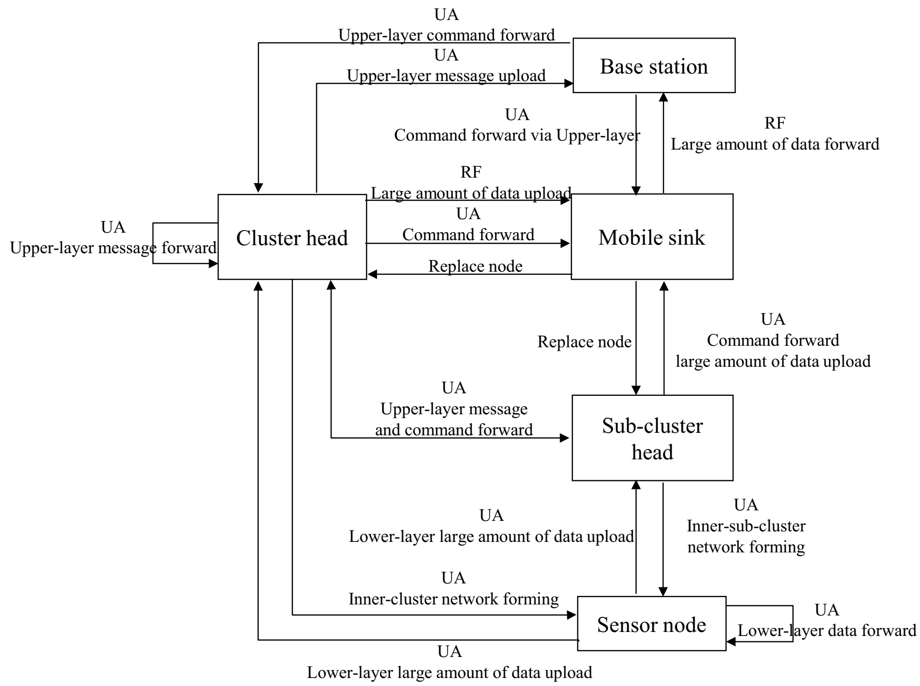


Fig. 2 Data forwarding direction and nodes status transfer diagram

$$\mathrm{SNR} = \mathrm{SL} - \mathrm{TL} - \mathrm{NL} + \mathrm{DI} \geq \mathrm{DT} \tag{1}$$

where SL, TL, NL, DI and DT represent source level of the transmitted sound wave, transmission loss, noise level, directivity index and detection threshold, respectively. TL over a distance d for a signal of frequency f is

$$\mathrm{TL} = 10\lg d + \alpha(f) \times d \times 10^{-3} \tag{2}$$

where $\alpha(f)$ is absorption coefficient in dB/km. It can be further calculated with the Thorp's expression [8] as follows:

$$\alpha(f) = \frac{0.011f^2}{1+f^2} + \frac{4.4f^2}{4100+f^2} + 2.75 \times 10^{-6} + 0.003 \tag{3}$$

Noise level NL is affected by sources of turbulence and wave noise. $\mathrm{NL} = 50 - 18\lg f$. Source level SL is the transmitted signal intensity I_T at 1 m distance away from the source:

$$\mathrm{SL} = 10\log\frac{I_T}{1\,\mu\mathrm{Pa}} \tag{4}$$

where $I_T = 10^{\mathrm{SL}/10} \times 0.67 \times 10^{-18}$. This intensity I_T requires the power transmitted by the source $P_T(d)$ [8]:

$$P_T(d) = 2\pi \times 1m \times H \times I_T \tag{5}$$

Table 1 The abbreviation of used symbols in network model

Abbreviation	Meaning of symbol
UMSN	Underwater mobile sensor networks
CSSP	CH–SH Selection and Sink Path-planning scheme
CH	Cluster head node in the network
SH	Sub-cluster head node in the network
AUV	Autonomous underwater vehicle
UA	Underwater acoustic communication
RF	Radio frequency communication
Upper-layer network	Multi-hop network consisting of CHs, SHs and base station, transmitting small amount of message and command among CHs, SHs and base station
Lower-layer network	Multi-hop network consisting of CHs, SHs and sensor nodes, forwarding large amount of data from nodes to CHs, and from nodes to SHs
v	Set of total sensor nodes in the network
v_{CH}^{j}	j-th Cluster head in the network
$v_{SH_i}^{j}$	i-th Sub-cluster head of the j-th cluster in the network
$d(v_{CH})$	Density of CH nodes in the network, which is CH number versus sensor nodes number
D_{Sink}	Maximum traveling distance of Sink moving path in a round trip
$D(v_i, v_j)$	Distance between node v_i and v_j
$P(v_i)$	Position coordinate of node v_i
$N(v)$	Number of sensor nodes in the network
$N(v_{CH})$	Number of assumed cluster head nodes in the network
$N^H(v_i)$	Number of one-hop neighbor nodes of v_i
$N^{In}(v_i)$	Number of inner-cluster (or inner-sub-cluster) nodes of v_i (v_i is CH or SH)
$E^H(v_i)$	Energy of one-hop neighbor nodes of v_i
$E^{In}(v_i)$	Energy of inner-cluster (or inner-sub-cluster) nodes of v_i (v_i is CH or SH)
$E_R(v_i)$	Remaining energy of sensor node v_i
$E_C(v_i)$	Consumed energy of sensor node v_i
$E_0(v_i)$	Initial energy of sensor node v_i

where d and H are the distances from the source and depth of the ocean. Finally, the energy E_C^{TX} for transmitting k bit over a distance d away from source is as below.

$$E_C^{TX} = P_T(d) \times T_{TX} \tag{6}$$

where T_{TX} is transmission time. This acoustic energy consumption model would be proposed in the following section.

4 Method

In this section, the proposed CH–SH Selection and Sink Path-planning scheme includes the CH position selection algorithm, SH selection algorithm, and mobile sink global & local-path-plan algorithm. The detailed description is as below.

4.1 Cluster head (CH) position selection algorithm

(1) *Fitness function calculation for CH position selection*

By the fitness function of CH selection, the PSO--based multi-objective optimization algorithm is used to sequentially calculate the optimal position of CH, in order to obtain the optimal CHs set $\{v_{\mathrm{CH}}^1, v_{\mathrm{CH}}^2, v_{\mathrm{CH}}^3, \ldots v_{\mathrm{CH}}^i\}$. Then, the mobile sink would sequentially move to each specified CH deployed position to place CH.

Firstly, the optimal deployed position $P(v_{\mathrm{CH}})$ of CHs would be calculated according to CHs number $N(v_{\mathrm{CH}})$. The number equation of CHs in the network is as follows:

$$N(v_{\mathrm{CH}}) = N(v) \times d(v_{\mathrm{CH}}) \tag{7}$$

where $d(v_{\mathrm{CH}})$ is the density of CH nodes. $N(v)$ is the number of network sensor nodes. The mobile sink would place CH according to CHs number.

Three factors are taken into consideration in this scheme when choosing CH v_{CH}^i: CH distance ratio $D'(T, v_{\mathrm{CH}}^i)$, CH energy ratio $E_R'^H(v_{\mathrm{CH}}^i)$, and CH neighbor number ratio $N'^H(v_{\mathrm{CH}}^i)$. After normalization, these factors would be calculated and optimized in the fitness function $f(v_{\mathrm{CH}}^i)$. The remaining energy, consumed energy and initial energy of a node are denoted as $E_R(v)$, $E_C(v)$, $E_0(v)$, and $E_R(v)+E_C(v)=E_0(v)$. The number and energy of one-hop neighbor nodes of v are denoted as $N^H(v)$ and $E^H(v)$. The number and energy of inner-cluster (or inner-sub-cluster) nodes of v are $N^{In}(v)$ and $E^{In}(v)$.

(1) CH distance ratio $D'(T, v_{\mathrm{CH}}^i)$ is the ratio of the sum of distance $D(T, v_{\mathrm{CH}}^i) = \sum_{j=1}^{i-1} D(v_{\mathrm{CH}}^j, v_{\mathrm{CH}}^i)$ between v_{CH}^i and T (the set of other selected CHs), to the maximum distance of sink moving path D_{Sink} in a round trip, the equation is as follows:

$$D'(T, v_{\mathrm{CH}}^i) = D(T, v_{\mathrm{CH}}^i)/D_{\mathrm{Sink}} = \sum_{j=1}^{i-1} D(v_{\mathrm{CH}}^j, v_{\mathrm{CH}}^i)/D_{\mathrm{Sink}} \tag{8}$$

where D_{Sink} presents the distance constraint of CH v_{CH}^i, which means that sum of total distance between CHs should not be longer than the sink trajectory length constraint D_{Sink}.

(2) CH energy ratio $E_R'^H(v_{\mathrm{CH}}^i)$ is the ratio of remaining energy $E_R^H(v_{\mathrm{CH}}^i)$ of v_{CH}^i's one-hop neighbor nodes to initial energy $E_0^H(v_{\mathrm{CH}}^i)$ of these nodes, the equation is as follows:

$$E_R'^H(v_{\mathrm{CH}}^i) = E_R^H(v_{\mathrm{CH}}^i)/E_0^H(v_{\mathrm{CH}}^i) \tag{9}$$

(3) CH neighbor number ratio $N'^H(v_{\mathrm{CH}}^i)$ is the ratio of one-hop neighbor nodes number $N^H(v_{\mathrm{CH}}^i)$ of v_{CH}^i to the total network nodes number $N(v)$, the equation is as follows:

$$N'^H(v_{\mathrm{CH}}^i) = N^H(v_{\mathrm{CH}}^i)/N(v) \tag{10}$$

Thereby, the fitness function $f(P(v_{\mathrm{CH}}^i))$ for the CH position selection is Eq. (11), which is improved from [24]. The larger value of $f(P(v_{\mathrm{CH}}^i))$ reflects the better position of candidate CH v_{CH}^i to be selected.

$$\begin{aligned} f(P(v_{\mathrm{CH}}^i)) &= D'(T, v_{\mathrm{CH}}^i) + E_R'^H(v_{\mathrm{CH}}^i) + N'^H(v_{\mathrm{CH}}^i) \\ &= \sum_{j=1}^{i-1} D(v_{\mathrm{CH}}^j, v_{\mathrm{CH}}^i)/D_{\mathrm{Sink}} + E_R^H(v_{\mathrm{CH}}^i)/E_0^H(v_{\mathrm{CH}}^i) + N^H(v_{\mathrm{CH}}^i)/N(v) \end{aligned} \tag{11}$$

Eq. (11) means that CH neighbor nodes number, neighbor remaining energy, and CH distance should be maximized. After calculating the quality value of candidate CHs position, the optimal CH position could be chosen.

$$f_{\mathrm{op}}(P(v_{\mathrm{CH}}^{i})) = \max(f(P(v_{\mathrm{CH}}^{1})), f(P(v_{\mathrm{CH}}^{2})), \ldots, f(P(v_{\mathrm{CH}}^{l}))) \tag{12}$$

where l is the number of total candidate CHs, and $i < l$. Then, the PSO algorithm is proposed to optimize calculating the CH selection fitness function $f(P(v_{\mathrm{CH}}^{i}))$, and the solution v_{CH}^{i} with max $f_{\mathrm{op}}(P(v_{\mathrm{CH}}^{i}))$ value would correspond to optimal CH position.

(2) *CH position selection optimization by PSO*

The particle swarm optimization (PSO) algorithm is provided to optimize the CH position selection for CSSP method. PSO is implemented by the existing CH nodes and would calculate the fitness to provide an optimal-fitness CH position. PSO could search for an optimal solution through each particle flying in the search space and adjusting its flying trajectory, according to its personal best experience and global best experience [25]. Owing to its simple structure and high efficiency, PSO has become a widely adopted optimization technique (Yang et al. [24] and Hu et al. [26]). The PSO searching space should be two dimensions, representing the two dimensions of CH position $P(v_{\mathrm{CH}}^{i})$. The network area is 20 km × 20 km, and the origin of the coordinate is shown in Fig. 3a. The algorithm process is as below.

(1) *Particle swarm position update*

In the PSO, each particle is a potential solution to the problem. Assume m_p particles fly in the two-dimensional search space, the position of the i-th particle is $x_i^t = (x_{i1}^t, x_{i2}^t)^T$, its velocity is $k_i^t = (k_{i1}^t, k_{i2}^t)^T$, and the iteration number is n_p. Thereby, in each time iteration t, velocity K and position X of each particle are updated by the following equations in [24]:

$$k_{id}^{t+1} = wk_{id}^{t} + c_1 rand_1(p_{id}^{t} - x_{id}^{t}) + c_2 rand_2(p_{gd}^{t} - x_{id}^{t}) \tag{13}$$

$$x_{id}^{t+1} = x_{id}^{t} + k_{id}^{t+1} \tag{14}$$

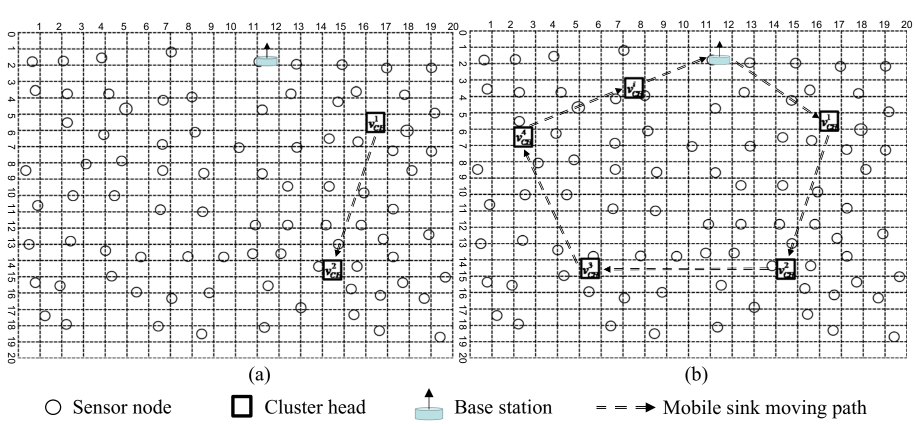


Fig. 3 The CHs position selection process in the UMSN model. **a** Initial CHs position; **b** Final CHs position

where c_1, c_2 are learning factors, and $c_1 = c_2 = 2$. $0 < d \le D$, $0 < i \le m_p$, $rand_1$ and $rand_2$ are uniformly distributed in [0, 1]. $p_i = (p^t_{i1}, p^t_{i2})$ is the best previous position of the particle, and $p_g = (p_{g1}, p_{g2})$ is the global best position of the whole particle swarm, which corresponds to the optimal deployed position of CH in Fig. 3a. Based on this position, the optimal fitness value of CH position $P(v^i_{\mathrm{CH}})$ can be calculated by Eq. (11).

In Eq. (13), w plays an important role in the convergence of the result among the adjustable parameters. To improve the system performance. The decreased weight w is proposed in [26].

$$w(t) = w_{\max} - (w_{\max} - w_{\min}) \times \exp\left(-\frac{p_{id}}{p_{gd}} \times \frac{1}{t}\right) \tag{15}$$

where $w_{\max} = 0.85$, $w_{\min} = 0.35$. When the iteration time increases, the weight would decrease, and a smaller $w(t)$ can ensure that the group eventually converges to the optimal position. As the particle global and personal best positions are both considered in Eq. (9), the weight $w(t)$ can change value adaptively according to the specific situation and obtain a better convergence value.

(2) *Termination criterion*

If the solution is satisfied with the termination condition: the fitness of function $f_{\mathrm{op}}(P(v^i_{\mathrm{CH}}))$ is the optimal fitness or iterations decrease from 100 to zero, the optimal CH v^i_{CH} position $P(v^i_{\mathrm{CH}})$ is calculated and selected, goto Step (3). Otherwise, return to Step (1). Then, the selected CHs set is $\{v^1_{\mathrm{CH}}, v^2_{\mathrm{CH}}, \ldots, v^i_{\mathrm{CH}}\}$.

(3) *Calculating next CH optimal position*

After Step (2), $i = i + 1$, and return to Step (1), the next CH v^{i+1}_{CH}'s position coordinate $P(v^{i+1}_{\mathrm{CH}})$ is calculated by fitness function $f(P(v^{i+1}_{\mathrm{CH}}))$, and optimal v^{i+1}_{CH}'s position is selected, until $i = N(v_{\mathrm{CH}})$. Thereafter, all the optimal CHs are selected.

An example is presented in Fig. 3a, b. When $i = 1$, the initial CH v^1_{CH} is placed in the network area. After the PSO iterative update, the next optimal CH's position $P(v^2_{\mathrm{CH}})$ is calculated by $f(P(v^2_{\mathrm{CH}}))$, and v^2_{CH} is selected. Then $i = i + 1$, the third optimal CH's position $P(v^3_{\mathrm{CH}})$ is calculated, until the i-th optimal CH's position $P(v^i_{CH})$ is calculated in order. Then, the selected CHs set is $\{v^1_{\mathrm{CH}}, v^2_{\mathrm{CH}}, v^3_{\mathrm{CH}} \ldots, v^i_{\mathrm{CH}}\}$, as shown in Fig. 3b, and the CH nodes position selection process is completed. Mobile sink would then move to the CH deployed area to place CHs according to the position of optimal CHs set.

4.2 Sub-cluster head (SH) selection algorithm

It is not enough to just set CH and sensor nodes for the proposed scheme, as if mobile sink only traverses CH among the clusters, mobile sink has to wait for all information to be retrieved from the node before moving to the CH. The multi-hop route also consumes much energy and increases node failure probability, and it is difficult to achieve a balanced energy consumption of nodes. For this reason, the sub-cluster network topology and sub-cluster head (SH) are provided. The CH would divide the cluster into several sub-clusters and select some nodes as SH by PSO algorithm, then SH could collect data from its inner-sub-cluster sensor nodes and reduce the multi-hop transmission distance of relay nodes. The SH selection algorithm is as below.

(1) *Fitness function calculation for SH selection*

After CHs have been deployed, the sub-cluster head nodes (SH) would then be selected from sensor nodes. The selection of the optimal SH from each cluster also depends on four factors: SH distance ratio $D'(v^i_{\mathrm{SH}_j})$, SH neighbor energy ratio $E'^H_R(v^i_{\mathrm{SH}_j})$, SH neighbor number ratio $N'^H(v^i_{\mathrm{SH}_j})$, and SH energy consumption ratio $E'^{In}_C(v^i_{\mathrm{SH}_j})$. The number of SHs in each cluster is assumed to be $N(v_{\mathrm{SH}}) = 4$. After normalization, these factors would be used to calculate the SH selection fitness function $f(v^i_{\mathrm{SH}_j})$.

(1) SH distance ratio $D'(v^i_{\mathrm{SH}_j})$ is the ratio of absolute value of distance $D(v^i_{\mathrm{CH}}, v^i_{\mathrm{SH}_j})$ between $v^i_{\mathrm{SH}_j}$ and v^i_{CH} minus $R_{\mathrm{CH}}/2$, to the CH communication radius R_{CH}.

$$D'(v^i_{\mathrm{SH}_j}) = \left|D(v^i_{\mathrm{CH}}, v^i_{\mathrm{SH}_j}) - R_{\mathrm{CH}}/2\right| \Big/ R_{\mathrm{CH}} \tag{16}$$

This equation means that the value of $D'(v^i_{\mathrm{SH}_j})$ is minimum and optimal value if distance between SH and CH is $R_{\mathrm{CH}}/2$.

(2) SH neighbor remaining energy ratio $E'^H_R(v^i_{\mathrm{SH}_j})$ is the ratio of $v^i_{\mathrm{SH}_j}$'s one-hop neighbor nodes' remaining energy $E^H_R(v^i_{\mathrm{SH}_j})$ to these node's initial energy $E^H_0(v^i_{\mathrm{SH}_j})$.

$$E'^H_R(v^i_{\mathrm{SH}_j}) = E^H_R(v^i_{\mathrm{SH}_j})/E^H_0(v^i_{\mathrm{SH}_j}) \tag{17}$$

(3) SH neighbor number ratio $N'^H(v^i_{\mathrm{SH}_j})$ is the ratio of $v^i_{\mathrm{SH}_j}$'s one-hop neighbor nodes number $N^H(v^i_{\mathrm{SH}_j})$ to the total inner-cluster nodes number $N^{In}(v^i_{\mathrm{CH}})$.

$$N'^H(v^i_{\mathrm{SH}_j}) = N^H(v^i_{\mathrm{SH}_j})/N^{In}(v^i_{\mathrm{CH}}) \tag{18}$$

(4) SH energy consumption ratio $E'^{In}_C(v^i_{\mathrm{SH}_j})$ is the ratio of energy consumption of data forwarded from all the inner-sub-cluster sensor nodes to this sub-cluster SH $E^{In}_C(v_{\mathrm{SH}})$, to the initial energy of these inner-sub-cluster nodes $E^{In}_0(v_{\mathrm{SH}})$.

$$E'^{In}_C(v^i_{\mathrm{SH}_j}) = E^{In}_C(v^i_{\mathrm{SH}_j})/E^{In}_0(v^i_{\mathrm{SH}_j}) = 1 - E^{In}_R(v^i_{\mathrm{SH}_j})/E^{In}_0(v^i_{\mathrm{SH}_j}) \tag{19}$$

The consumed energy of inner-sub-cluster sensor nodes can be calculated according to acoustic energy consumption model of Sect. 2.2. Therefore, the fitness function $f(v^i_{\mathrm{SH}_j})$ for the optimal SH selection is as follows:

$$\begin{aligned} f(v^i_{\mathrm{SH}_j}) &= (N'^H(v^i_{\mathrm{SH}_j}) + E'^H_R(v^i_{\mathrm{SH}_j}))/(D\prime(v^i_{\mathrm{SH}_j}) + E'^{In}_C(v^i_{\mathrm{SH}_j})) \\ &= \frac{\frac{N^H(v^i_{\mathrm{SH}_j})}{N^{In}(v^i_{\mathrm{CH}})} + \frac{E^H_R(v^i_{\mathrm{SH}_j})}{E^H_0(v^i_{\mathrm{SH}_j})}}{\frac{\left|D(v^i_{\mathrm{CH}}, v^i_{\mathrm{SH}_j}) - R_{\mathrm{CH}}/2\right|}{R_{\mathrm{CH}}} + 1 - \frac{E^{In}_R(v^i_{\mathrm{SH}_j})}{E^{In}_0(v^i_{\mathrm{SH}_j})}} \end{aligned} \tag{20}$$

Eq. (20) means that the number and remaining energy of neighbor nodes of SH should be maximized; meanwhile, the distance between SH and CH, and energy consumption of inner-sub-cluster should be minimized. After calculating the quality value of candidate SH, the optimal SH could be chosen by the PSO algorithm.

$$f_{\text{op}}(v^i_{\text{SH}_j}) = \max(f(v^i_{\text{SH}_1}), f(v^i_{\text{SH}_2}), ..., f(v^i_{\text{SH}_k})) \quad (21)$$

where k is the max number of candidate SH nodes, and $j < k$.

(2) *SH selection optimization by PSO*

The PSO algorithm calculates SH fitness function (20) to provide optimal fitness SHs. In the PSO, each particle is a potential solution, and the optimal solution value of SH $v^i_{\text{SH}_j}$ can be calculated by Eqs. (13) and (14). Then, $j = j + 1$, and each optimal SH $v^i_{\text{SH}_j}$ is selected, until $j = N(v_{\text{SH}}) = 4$. Thereby, all the optimal SHs in i-th cluster are selected.

(3) *Upper-layer network forming*

After CHs and SHs have been selected, the CHs, SHs and base station form the upper-layer multi-hop network, to achieve large communication area coverage of seabed plane. As the UA communication distance of CHs is much longer than sensor nodes, the CH can forward information to base station via multi-hop route formed by CHs. As SHs can connect with CHs directly, SHs could also be added to this upper-layer network. Therefore, the upper-layer network can only transmit small amount of event messages and commands among CHs, SHs and base station using UA communication (such as route $v^2_{\text{SH}_4}$->v^2_{CH}->v^1_{CH}->Base station in Fig. 4). The link direction from base station to CH or from CH to the SH is defined as the downlink direction, and the reverse direction is defined as the uplink direction. The base station would forward the local-path-plan command to downlink direction, and each CH or SH would temporarily forward event message to uplink direction.

When the CH or SH in upper-layer network has sent a packet to neighbors and could not receive reply packet, it would repeat data retransmission two times, until it receives the reply packet. This mechanism is called the Retransmission Mechanism, which could make sure that the packet would be delivered successfully. There is also a Heartbeat Mechanism to maintain the upper-layer link between CHs and SHs continuously, and the Heartbeat packet would be delivered using UA communication every *T'* interval.

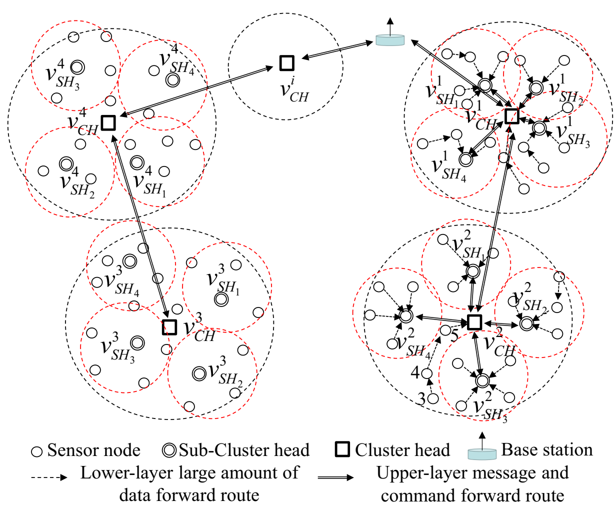


Fig. 4 Cluster and sub-cluster network forming model in the UMSN

Once a CH or SH could not receive the reply packet from neighbor after it sent the Heartbeat packet to its neighbor, it would use retransmission mechanism to retransmit Heartbeat packet up to 5 times. If this CH or SH still could not receive reply packet, it would consider that its neighbor is failed and upload this neighbor node failure message to the base station from available upper-layer uplink route. The upper-layer network is responsible for delivering small amount of messages and commands.

(4) *Lower-layer network forming*

After the upper-layer network has been formed, the lower-layer network in each cluster would be constructed by the CH, SHs and sensor nodes. In the cluster v_{CH}^{i}, the sensor nodes belonging to a sub-cluster would forward large amount of data to this SH via multi-hop route (such as 1->2->$v_{\mathrm{SH}_2}^{2}$ in Fig. 4), due to the limited communication distance of sensor node. The other nodes that do not belong to any sub-clusters would forward large amount of data to v_{CH}^{i} via multi-hop route (such as 3->4->5->v_{CH}^{2} in Fig. 4). The CHs and SHs would collect and store data from sensor nodes, waiting for mobile sink to request data. The lower-layer network is responsible for delivering large amount of collected data.

4.3 Mobile sink global and local-path-plan

(1) *Global-path-plan for mobile sink*

After upper-layer and lower-layer networks have both been formed, the base station would call the TSP solver (a local-search-based DTSP solver mentioned by the authors of [27]) to calculate and plan the shortest global moving path for mobile sink, so that the sink would visit all the CHs and SHs. Therefore, the sink can obtain the shortest-length global path and save energy.

Afterward, the mobile sink would move and reside nearby each CH and SH according to the shortest planned path. It would receive and store data from CH using RF communication, and from SH using acoustic communication. Then, it moves to the next CH or SH, until all the CHs and SHs are traversed by the mobile sink (such as path $v_{\mathrm{SH}_1}^{1}-v_{\mathrm{SH}_2}^{1}-v_{\mathrm{CH}}^{1}-v_{\mathrm{SH}_3}^{1}-v_{\mathrm{SH}_4}^{1}-v_{\mathrm{SH}_1}^{2}-v_{\mathrm{CH}}^{2}-v_{\mathrm{SH}_2}^{2}-v_{\mathrm{SH}_3}^{2}-v_{\mathrm{SH}_4}^{2}-v_{\mathrm{SH}_1}^{3}-v_{\mathrm{SH}_2}^{3}\cdots$ in Fig. 5). At last, the mobile sink would visit the base station and upload the stored data to it using RF communication, as described in Fig. 5. Then, it would restart the next round trip.

(2) *Local-path-plan for mobile sink*

(1) When one of SHs or CHs detects an emergency event (such as important event occurred in an area around v_{CH}^{2} in Fig. 5), it would report to base station via upper-layer data delivery route (v_{CH}^{2}-v_{CH}^{1}-Base station in Fig. 4). After the analysis and evaluation, base station will decide whether to focus on monitoring this area and broadcast local-path-plan command to all the CHs and SHs via an upper-layer multi-hop route. When the mobile sink moves close to any CH or SH, it will receive the command from this CH or SH ($v_{\mathrm{SH}_4}^{3}$ in Fig. 5) and immediately move to the requested area to collect data according to the command. After its urgent data collecting task, the mobile sink would

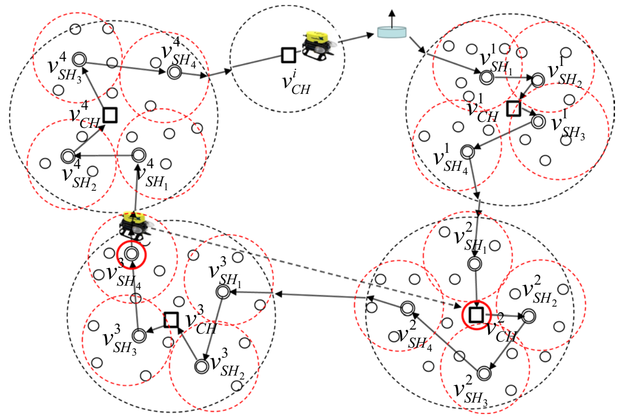


Fig. 5 Global and local-path-plan diagram of mobile sink

continue its global moving path. This scheme can prolong the controlling distance of base station over mobile sink.

(2) When the remaining energy of a certain CH is too low or it is failed (v_{CH}^2 in Fig. 5), its neighbor CH will detect it by heartbeat mechanism and report to the base station via upper-layer route. After analysis and evaluation, base station will decide to replace this CH or SH node and broadcast local-path-plan command to all the CHs and SHs via upper-layer route. When the mobile sink moves close to any CH or SH, it will receive the command from the CH or SH ($v_{\mathrm{SH}_4}^3$ in Fig. 5). Then, it immediately moves to the requested position to replace this node with an alternative node according to the command. After its urgent task, the mobile sink would continue its round trip. This mobile sink global and local-path-plan algorithm can achieve efficient packet delivery and maintain stable network communication links.

5 Simulation results and discussion

In this section, the simulation experiment setting is described, the simulation results and the method performance analysis are discussed, and the algorithm complexity is finally analyzed.

5.1 Experimental setting

To evaluate the CSSP performance with simulation-based experiments, the simulation is conducted in an environment based on Matlab 2010a. The experimental hardware environments are Intel®i7-4600 M, 2.90 GHz CPU and 4 GB memory, the operating system is MS windows 7. The whole network is simulated in an area of 20 km × 20 km, 200–300 sensor nodes are placed in this area uniformly. The number of CHs is 6–10, the number of SHs in each cluster is 4, and a mobile sink moves in this area at speed of 1 m/s. All sensor nodes have the same initial energy of 2500 mAH, the acoustic communication distance is 0.5 km. Each sensor node would deliver large amount of data to CHs and SHs via multi-hop route at the rate of 20 packets per round. Each data packet size is 1 KB, and each round of simulation lasts 20 min. The CHs also generate large amount of data at the rate of 10 MB per round and upload to the mobile sink when the sink moves to the communication range of CH. The failure probability of CH and SH is 0.01, which can be used to evaluate the CHs link recovery ability and network robust performance. The whole simulation experiments last 10 times, and a one-time simulation includes 300 rounds, then the simulation results are the average values of 10 times simulation.

The proposed CSSP scheme is compared with the other three typical underwater sensor networks schemes, including the scheme using AUV to visit all nodes (AA-RP protocol by Wang [18]), the clustering-based scheme (ACMC protocol by Huang [19]), and the scheme based on sub-cluster-network (PNG protocol by Khan [22]). The performance metrics used for comparison are energy consumption ratio (the ratio of consumed energy of all the nodes, to the initial energy of all the nodes), standard deviation of energy consumption (the standard deviation of consumed energy of all the nodes), and packet delivery ratio (the ratio of number of received packets by mobile sink, to the number of data packets sent from the nodes).

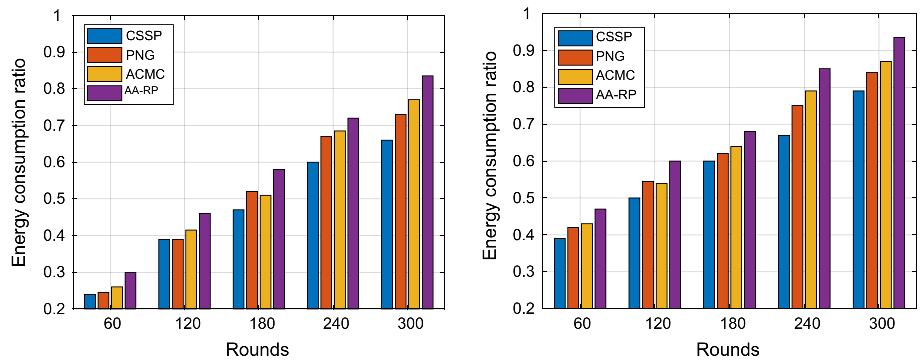
In the simulation, standard deviation (SD) is used to measure the imbalance between the nodes' energy consumption. A wider variation means that some nodes of the network would run out of energy faster. The metric SD is calculated as follows:

$$\mathrm{SD}(v) = \sqrt{\sum_{N(v)}^{i=1} (E_C(v_i) - \mu(v))/N(v)} \tag{22}$$

where $E_C(v_i)$ is the energy consumption of node v_i, v is the sensor nodes set, $\mu(v)$ is the average energy consumption of all sensor nodes.

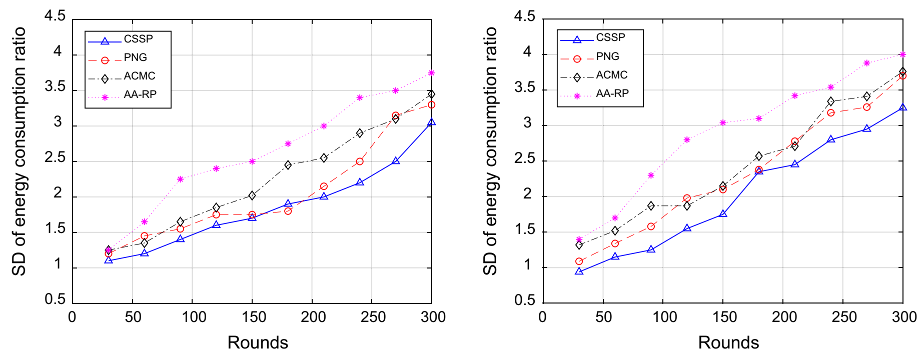
5.2 Performance analysis and discussion

Figure 6 shows the curve trend of energy consumption ratio for these protocols with different sensor nodes number. The nodes number of Fig. 6a, b are 200 and 300, CHs number and SHs number remain at 6 and 24. Experimental results in Fig. 6a demonstrate that compared with the typical data gathering scheme AA-RP that used mobile sink to visit all nodes, the CSSP scheme reduces energy consumption of data collection by 22%. Compared with the clustering-based scheme ACMC and sub-cluster-based scheme PNG, the CSSP scheme reduces energy consumption of nodes by 16% and 11% and improves network lifetime. The reason is that the CSSP scheme can select CHs and SHs with better QoS parameters (such as more remaining energy, more suitable distance from other CHs, and more neighbor nodes), and faster convergence speed by particle swarm iterative optimization, to plan optimal global and local-path of mobile sink. Thus, a more reliable data delivery route from sensor nodes to CHs /SHs could be built to save energy. The SHs mechanism can reduce the average multi-hop transmission distance of relay nodes and save energy, the multi-mode communication mechanism also helps to reduce communication and energy overhead. The results also show that the energy consumption of scheme using sink to visit only cluster head or sub-cluster head is much lower than the scheme using sink to visit all nodes. By comparing Fig. 6a with 6b, it is obvious when number of sensor nodes increases from 200 to 300, the network routing would be reconstructed more frequently, and the energy consumption and node communication costs are



(a) Nodes number 200 (b) Nodes number 300

Fig. 6 Comparison of energy consumption for different number of sensor nodes. **a** Nodes number 200; **b** Nodes number 300



(a) Nodes number200 (b) Nodes number 300

Fig. 7 Comparison of SD of energy consumption for different number of sensor nodes (a) Nodes number 200; (b) Nodes number 300

increased. However, CSSP still achieves lower energy consumption value than AA-RP [18], ACMC [19] and PNG [22], which means that CSSP scheme can efficiently solve the CH–SH selection optimization problem and global & local-path-plan problem of mobile sink.

The performance of the four protocols for balancing energy consumption is shown in Fig. 7. Figure 7a, b shows the curve trends of SD of node energy consumption as the number of nodes increases from 200 to 300. The nodes number of Fig. 7a is 200, the nodes number of Fig. 7b is 300, and the numbers of CHs and SHs remain at 6 and 24. Observation shows that the SD of node energy cost of CSSP scheme is 9%, 12% and 19% lower than PNG [22], ACMC [19] and AA-RP [18]. The SD values of cluster-based PNG and ACMC protocols are almost the same. As in the CSSP, the selected CHs and SHs would be more evenly distributed and balance the energy consumption of sensor nodes. The moving sink can quickly replace and repair the failed nodes and maintain the network robustness, it would make lower SD of energy consumption by comparing with AA-RP, ACMC and PNG. The SD results demonstrate that the energy balance of schemes using mobile sink only visit cluster head or sub-cluster head could be better than the scheme using mobile sink to visit all nodes. When the number of sensor nodes is increased, the SD of four protocols could get an average increase of 8–10% in Fig. 7b, and the energy consumption of the CSSP protocol is more balanced than PNG [22], ACMC [19], and AA-RP [18]. This result presents that increased sensor nodes would lead to greater network overhead, make some nodes consume more energy, but CSSP demonstrates its stronger ability to avoid energy hole problems and balance network overhead.

Figure 8a, b compares the packet delivery ratio of four protocols when the number of CHs increases from 6 to 10 (CHs number of Fig. 8a is 6, CHs number of Fig. 8b is 10), which means that number of SHs also increases from 24 to 40, and the number of all the sensor nodes remains at 200. The results are shown that the packet delivery ratio drops as the number of simulation rounds is increased. This is because the instability of underwater acoustic communication links would increase the lost number of packets and affects quality of the UMSN, which would decrease the number of successfully delivered packets. Comparing with the sub-cluster-based PNG protocol [22], clustering-based ACMC protocol [19] and typical AA-RP protocol [18], the CSSP obtains 8%, 10% and 12% higher packet delivery rate, respectively. This is due to the multi-modes (acoustic and RF) communication mechanism, by which data can be delivered to the mobile sink more effectively. The more suitable head nodes would also be selected by the particle swarm iterative optimization, to transmit data more efficiently. In addition, as the upper-layer multi-hop routes could be provided to send local-path-plan control command and change sink moving path, this scheme can replace failed nodes efficiently, to reduce the packet loss rate and prolong the network lifetime. The simulation results also demonstrate that the data delivery ratio of schemes using mobile sink visit SHs and CHs (CSSP) is higher than the clustering scheme that mobile sink only visits CHs (ACMC). When the number of CHs is increased compared with Fig. 8a, b, the packet delivery ratio is also increased, since greater number of CHs would reduce the average hops number of routes from inner-cluster sensor nodes to their CHs and SHs. The failure probability of node links of CSSP is smaller than other selected protocols (AA-RP results would not change as mobile sink still visits all nodes), which demonstrates the potential of the CSSP to play more important role in enhancing underwater data gathering efficiency.

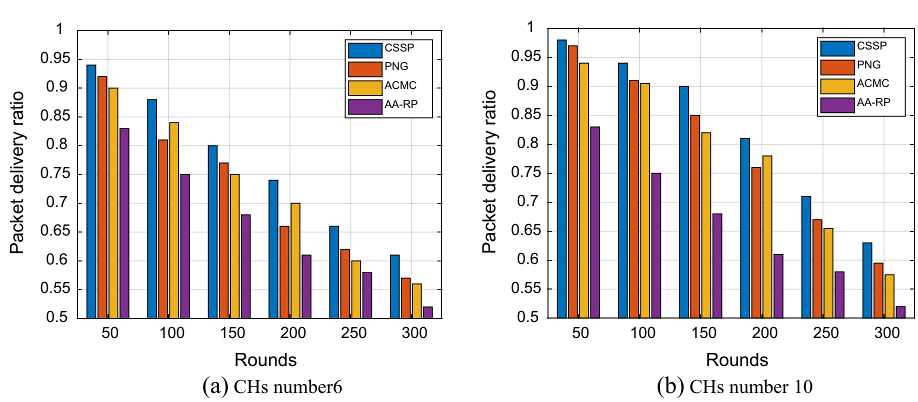


Fig. 8 Comparison of packet delivery ratio for different number of CHs (a) CHs number 6; (b) CHs number 10

5.3 Algorithm complexity analysis

In the proposed CH–SH Selection and Sink Path-planning scheme, PSO algorithm is its core algorithm and consumes the most computing resources. Computational complexity is an important performance index to measure this algorithm. The particle number of PSO is assumed to be m_p, the number of iterations is n_p, and each operation time is t_p. The average time required for MPSO to complete optimization is $m_p \times n_p \times t_p$. Therefore, the computational complexity of MPSO is $O(m_p \times n_p)$, which indicates that the iteration number and particle size have direct impact on the search speed of the algorithm.

As there are no intelligent algorithms in the other three types of protocols, the computing cost and computational complexity of CSSP would be higher than these protocols. However, the multi-group PSO algorithm of CSSP method is an easy and simple implementation and is highly adaptable to solve this optimization problem, which would quickly select optimal head nodes to balance network energy, and cause lower communication cost in the network. It is obvious that communication consumption is much larger than computing consumption in the proportion of network energy consumption, so CSSP would consume less energy than other typical protocols. Simulation results of Figs. 6 and 7 verified that CSSP scheme was 9%, 12% and 19% lower than PNG, ACMC and AA-RP in terms of energy consumption, 9%, 12% and 19% lower than PNG, ACMC and AA-RP in terms of SD of energy consumption, which presented the performance of CSSP scheme for reducing and balancing energy consumption.

6 Conclusion

Aiming at collecting data efficiently from UMSN and avoiding imbalance of network overhead and energy, this paper presents an energy-balanced head nodes selection scheme (called CSSP). Firstly, it provides a three-layer sensor network topology to collect underwater environment data, in which sensor nodes forward large amount of data to the CH and SH via lower-layer multi-hop route. The mobile sink would move and visit all the SHs and CHs to collect data, to reduce the multi-hop acoustic transmission distance of relay nodes, and avoid energy hole. CHs collect large amount of multimedia data and upload to the mobile sink at high data delivery speed using RF communication, which is beneficial to saving network energy and expanding network coverage area. Secondly, the particle swarm iterative optimization could select the optimal CHs and SHs, which can balance energy of UMSN. Thirdly, the base station could send the remote local-path-plan command to the mobile sink via upper-layer route, which effectively realizes long-distance real-time control over mobile sink. Thereby, these heterogeneous nodes can cooperatively collect underwater environmental data and maintain network communication. The simulation results verified that the proposed CSSP scheme outperformed 11%, 16% and 22% over three typical protocols in terms of nodes energy consumption, CSSP was 9%, 12% and 19% lower than three typical protocols in terms of SD of energy consumption, packet delivery ratio of CSSP was 8%, 10% and 12% higher than three typical protocols. This proposed scheme can efficiently achieve robust data transmission and solve the bottleneck problem of the underwater communication speed and distance conflict.

In the future, we will focus on global and local moving path-plan of underwater multi-sinks (AUVs), and the acoustic link stability problem for higher-speed communication by using other types of simulators, such as NS3. We will also apply the underwater sensors nodes using acoustic telemetry modem ATM-885 to the real test, to verify performance of the proposed protocol. USV (unmanned surface vessel) and subsurface buoy would also be applied to the proposed UMSN, to form the ocean 3D network monitoring system and application scenarios, such as Marine ranching application.

Abbreviations

UMSN	Underwater mobile sensor networks
CSSP	CH–SH Selection and Sink Path-planning Scheme
CH	Cluster head node in the network
SH	Sub-cluster head node in the network
AUV	Autonomous underwater vehicle

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Author contributions
YH finished the algorithm design and part of experiments, and English writing of the paper. KH and HL corrected the paper grammar and completed part of experiments. XW suggested some modifications and checked some English writing grammar. All authors read and approved the final manuscript.

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Availability of data and materials
Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Competing interests
The authors declare that they have no competing interest.

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