# A Deployment Optimization Mechanism Using Depth Adjustable Nodes in Underwater Acoustic Sensor Networks

Zhigang Jin, Zhihua Ji, Yishan Su
*School of Electrical and Information Engineering*
*Tianjin University*
Tianjin, China
*{zgjin, yishan.su}@tju.edu.cn, zhihua_ji@163.com*

Shuo Li
*School of Engineering*
*RMIT University*
Melbourne, Australia
*shuo.li2@rmit.edu.au*

*Bo Wei*
*Waseda University*
*Tokyo, Japan*
*weibo0504@fuji.waseda.jp*

***Abstract*—The past few years have witnessed a significant progress in the research of underwater acoustic sensor networks. However, most studies on network deployment can only achieve excellent coverage with isolated connectivity or excellent connectivity with coverage holes in the monitoring area. Both coverage and connectivity are important to guarantee the quality of monitoring in Underwater Acoustic Sensor Networks (UASNs). To achieve the joint optimization of network coverage and connectivity, we proposed a deployment optimization mechanism using depth adjustable nodes in UASNs. The sink nodes are evenly distributed on the water surface and act as cluster heads. The sensor nodes in a cluster are adjusted vertically to form the topology with the sink node as the root node so that all nodes in the network are connected. Network deployment is optimized by finding the optimal location of node, with the network topology remains the same as a constraint. Simulation results show that our proposed deployment mechanism can achieve higher coverage with all nodes connected.**

***Keywords—underwater acoustic sensor network, connectivity, coverage, node deployment,***

## I. INTRODUCTION

Underwater Acoustic Sensor Networks, as a new way to explore and exploit oceans, are widely used in many fields such as marine information collection, geological disasters prevention, resources exploration and military monitoring. In recent years, the research of UASNs mainly focuses on underwater communications technology, protocols design, deployment, location tracking and security [1]. The deployment of nodes can not only influence the coverage and connectivity of the network, but also affect the design of multi-layer protocols such as MAC and Routing. For example, when AUVs are deployed in the underwater networks, the impact of AUV mobility on the routing protocol needs to be considered; in case of the uneven deployment of nodes, MAC protocol can choose different access control methods to optimize network capacity according to different node density. It is of great significance to study an effective deployment mechanism. However, compared with node deployment in traditional wireless sensor network, new features such as three-dimensional (3D) deployment space, unstable network topology and the sensor node battery is not easy to replace pose great challenges to the design of network deployment mechanism in UASNs [2].

Depending on the mobility capability, underwater sensor nodes can be classified into three categories, namely static, free-mobile and limited□mobile nodes. For example, unmanned or autonomous underwater vehicles such as ROVs and AUVs are typical free-mobile nodes. In general, an ROV/AUV node is equipped with a motor unit and can move to any location and depth. However, a motor unit is generally expensive. In some scenarios, a 3D underwater region needs to be continuously monitored. A common approach is to place many cheap nodes permanently at different depths of this 3D space. An example of such node was proposed in [3], where a Mica2 mote is put in a cylinder which has a piston for drowning water in and draining water out. It is a kind of limited-mobile nodes. As water pumps in, the node starts sinking; and as water moves out, it starts rising. In this way, we can adjust the depth of an underwater sensor node. With its mobility, this node can not only reduce deployment time, labor and other costs more efficiently, but also make it easier to optimize network coverage and connectivity.

Both coverage and connectivity are important to guarantee the quality of monitoring in UASNs. Effective coverage ensures that the network performs a complete and accurate collection of information on the target area, connectivity directly determines perception information of nodes can be effectively transmitted to the data center or not. To achieve the joint optimization of network coverage and connectivity, we proposed a deployment optimization mechanism using depth adjustable nodes (DODA) for UASNs. Our proposed deployment mechanism can achieve higher coverage with all nodes connected.

The rest of the paper is organized as follows. In section II, we briefly introduce the related work of network deployment in UASNs. A detailed description of the mechanism is presented in section III. In section IV, some simulation experiments were done to show the effectiveness of the mechanism. Finally, conclusions are drawn in section V.

## II. RELATED WORK

Many techniques have been proposed to solve the network deployment problem in UASNs for the past few years. They are typically classified into three main categories based on the

This work was supported by the National Natural Science Foundation of China (Grant Nos. 61571318 and 61701335) and the Tianjin Natural Science Foundation of China (Grant No. 17JCQNJC01300).

978-1-5386-1654-3/18/$31.00 ©2018 IEEE

mobility of nodes, namely, static deployment, free-mobile deployment, and limited-mobile deployment, respectively [4]. The static deployment algorithm is based primarily on the mathematical theory deduction. It assumes that nodes are immovable and fixed at specific locations manually. D. Pompili purposed an exhaustive search-based Maximum Coverage Optimization Algorithm to determine the minimum number of sensors to be deployed. As long as the search step is small enough, the algorithm can achieve the theoretical limit of the maximum coverage efficiency [5]. However, this algorithm does not consider such factors as deployment cost and environmental impact. In reality, the network topology is often changed due to factors such as ocean current, aquatic creatures and so on, so the effect of achieving the maximum coverage with a minimum number of nodes cannot be guaranteed.

The mobile nodes can make network deployment easier to optimize, enhance the robustness of the network and reduce the difficulty of the late topology maintenance by dynamically adjusting their location. Almutairi proposed a 3D virtual forces deployment (TVFD) algorithm [6]. It translates the distance among nodes into a virtual force on the node and optimizes the coverage by moving nodes using the virtual force. N. Xia put forward the particle swarm inspired node deployment (PSIND) algorithm [7]. It drives sensor nodes to cover the events and make the distribution of sensors match that of events by simulating the flying behavior of particles and introducing crowd control. Although above algorithms could improve network coverage rates, it could not ensure full network connectivity, and they are easy to fall into the problem of local optimization. In [8], the wolf search algorithm is used as the basis for node movement, they simulate the wolf hunting to optimize the coverage and the avoidance mechanisms to avoid local optimization and obstacles. This kind of algorithm makes full use of behavioral features of animals and tries to cover events as many as possible. However, only AUVs can easily move in any direction at present, while AUVs are expensive and networking with a large number of AUVs is not of great value [9].

Based on the limited-mobile nodes, K. Akkaya proposed a distributed node deployment algorithm [10]. This algorithm divides nodes whose coverage are overlapped into different groups and determines whether to adjust the depth of nodes and how to adjust by the goal that minimize the overlap among nodes. However, the algorithm only pursues the coverage optimization without considering the effective connectivity among nodes. Delaunay triangulation is used in [11] to calculate the distance between adjacent layers so as to optimize the connectivity of nodes. However, the deployment method based on Voronoi diagram makes it easy for the neighboring nodes to dive together so as to form the holes of coverage. Through the above analysis we can see that both coverage and connectivity are the key aspects of the network deployment, so we should optimize them together so as to improve the network performance.

## III. Mechanism Description

Our proposed deployment optimization mechanism consists of two phases. The first phase is to build a tree topology by depth adjustment. The second phase is to adjust the node location using neighbors' information to optimize the coverage of network.

Initially, sensor and sink nodes are randomly and uniformly distributed on the surface of water respectively and the size of target monitoring water is $L \times W \times H$. Then the 3D topology structure is formed through depth adjustment of sensor nodes. In the UASNs work process: sensor nodes under the water surface use acoustic communication to transmit information, they transmit the collected information to the sink nodes through single-hop or multi-hop paths, and then sink nodes transmit the information to the data center through satellite or terrestrial base stations for analysis [12].

The network scenario is shown in Fig. 1.

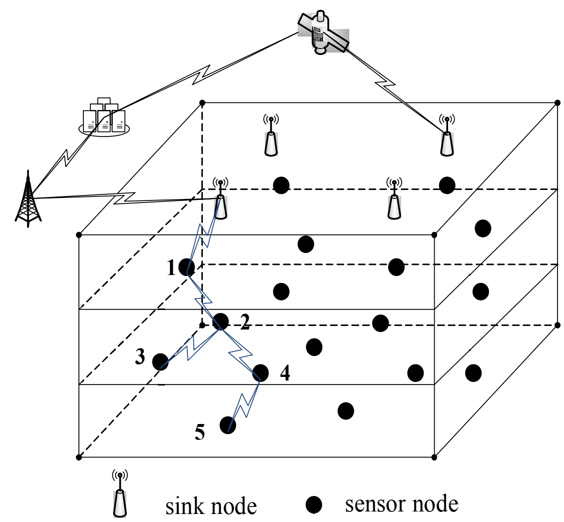


Fig. 1. Network scenario

Some preliminaries are proposed as follow:

(1) In reality nodes may move under the influence of external factors such as ocean currents, marine organisms and so on. However, in view of the strong correlation among nodes movement [13], it is considered that the positional relationship among nodes is relatively fixed in this paper;

(2) All nodes know their initial two-dimension coordinates and can only move in the vertical direction;

(3) All sensor nodes have the same communication and perceived radius, and the communication radius is greater than the perceived radius;

(4) Questions such as effective communication among nodes, positioning and other issues in mechanism can be solved by related technologies [14];

### *A. Phase one: Tree Building*

In this section, we describe the tree building of the mechanism in detail, the related symbols are defined as follows：

TABLE I. SYMBOL DEFINITION

| Parameter Names | Symbol |
|---|---|
| Set of sink nodes | $\boldsymbol{S}$ |
| Set of sensor nodes | $\boldsymbol{N}$ |
| Horizontal distance between sink $s_m$ and sensor node $n_i$ | $d_{mi}$ |
| Cluster which number is $t$ | $C_t$ |
| Perception radius of sensor nodes | $r$ |
| Ratio of node communication and perception radius | $k$ |
| Vertical distance between nodes whose sequence numbers are $i$ and $i$+1 | $d(i,i+1)$ |
| Set of depths of nodes | $\boldsymbol{H}$ |
| Depth of node whose number is $i$ | $depth_i$ |
| Maximum depth of the target water | $depth_{\max}$ |

The sink node $s_i$ ($s_i \in \boldsymbol{S}$)broadcasts a beacon with cluster ID within its communication range, itself as the head of the cluster. The sensor node $n_i$ ($n_i \in \boldsymbol{N}$) chooses the nearest one away from it to join in and reply an ACK message to confirm. The formula is as follows:

$$C_t = \{ n_i \mid d_{ti} = \min(d_{1i}, d_{2i}, ..., d_{mi}) \} \tag{1}$$

Then nodes begin to number in clusters, sink node determines the nearest sensor node away from it as the first node, the first node determines the nearest sensor node away from it as the second node, and so on until all sensor nodes in this cluster have their own sequence number.

The target depth of the sensor nodes is calculated by equations (1) and (2). After calculation, the sink node sets the state of all the sensor nodes in its cluster for completion.

$$depth_{i+1} = depth_i + d(n_i, n_{i+1}) \tag{2}$$

$$d(n_i, n_{i+1}) = \sqrt{(k \cdot r)^2 - \left[ (x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 \right]} \tag{3}$$

When there is further depth for a node to descend, this node chooses an existing depth from $H = \{h_1, h_2, ..., h_k\}$, where the other nodes in the same cluster have the largest horizontal distance from it to reduce overlap among them.

After depth adjustment, node $n_i$ selects a node whose depth is less than $depth_i$ and distance is less than $k \cdot r$ and connected the selected node to itself as its parent node, own as the child node. If there is no suitable node, it will choose the closest node that is at the same depth as its parent node, own as the child node.

When the first phase is completed, the tree topology with the sink node as the root node is formed. Any node in the topology can transmit the collected information to the root sink node through one-hop or multi-hop so as to ensure all nodes connected.

Procedure of the first phase is shown in Fig. 2.

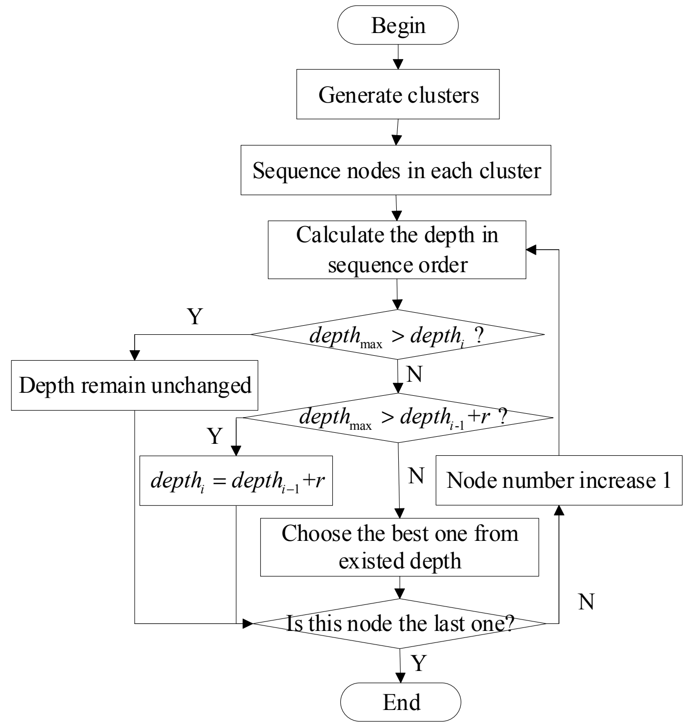


Fig. 2. The flow chat of the first phase

*B. Phase two: Coverage Optimization*

Trees can only guarantee the connectivity among nodes. It cannot optimize the performance of network coverage. Therefore, sensor nodes are adjusted in the vertical direction to increase the coverage of network in this phase. When a node is adjusted, it only exchanges location information with its neighbors, which helps to reduce the number of calculation of nodes and speed up the convergence of the network. The set of neighbors $\boldsymbol{Q}_i$ of node $n_i$ includes all the nodes within the communication range of $n_i$.

The objective function of coverage optimization based on the system model can be expressed as:

$$\min \left\{ \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{l} V_{ij} \right\} \tag{4}$$

where $V_{ij}$(z) represent the overlapping volume between nodes $n_i$ and its neighbor $n_j$.

However, by analyzing the node deployment problem, we find that we cannot find a network range optimal solution in polynomial time. It can be regarded as an NP-hard problem, so we optimize the coverage of each node by node traversal.

Assuming that the depth of node $n_i$ is $z$, the objective function of node $n_i$ can be expressed as:

$$\min V_{ia}(z),\quad V_{ia}(z)=\sum_{j\in Q_i} V_{ij}(z) \tag{5}$$

where $V_{ia}(z)$ represent the total perceived overlapping volumes between node $n_i$ and its neighbors when the depth of node $n_i$ is $z$.

The equation for calculating $V_{ij}$ is:

$$V_{ij}=\begin{cases} \frac{\pi}{12}d_{ij}^3-\pi r^2 d_{ij}+\frac{4}{3}\pi r^3, & d_{ij}<2r \\ 0 & ,d_{ij}\geq 2r \end{cases} \tag{6}$$

where $d_{ij}$ represents the distance between nodes $n_i$ and $n_j$. The range of $z$ is calculated by:

$$d(parent/child \text{ of } n_i,\ n_i)<k\cdot r \tag{7}$$

$$z<depth_{\max} \tag{8}$$

Obtain the optimal solution of the function in the range of $z$, then the node $n_i$ moves to the appropriate depth.

Procedure of the second phase is shown in Fig. 3.

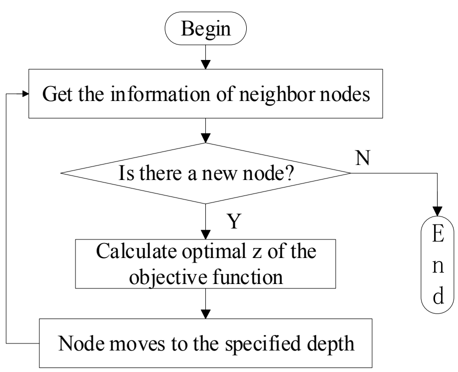


Fig. 3. The flow chat of deployment optimization

## IV. Simulation

In this section, we evaluate and compare the performance of three other deployment algorithms (DASD [10], VBDA [11] and random) with DODA. The perception model of the nodes is Boolean. The network connectivity rate $Con$ can be defined as the ratio of $n_s$ and $n_t$, the equation is as follow:

$$Con=\frac{n_s}{n_t} \tag{9}$$

where $n_t$ is the total number of sensor nodes and $n_s$ is the number of nodes that can communicate with the sink nodes through single-hop or multi-hop.

To calculate the network coverage, the deployment area is divided into many small cubic lattices and the detection point is located at the center of each cubic lattice. The network coverage rate $Cov$ can be defined as the ratio of $N_t$ and $N_s$, the equation is as follow:

$$Cov=\frac{N_s}{N_t} \tag{10}$$

where $N_t$ is the total number of all cubic lattices and $N_s$ is the number of cubic lattices whose information can be accepted by sink nodes.

The network is deployed in waters of 6km×6km×3km. Among them, 9 sink nodes are uniformly distributed on the surface of the target waters, and the horizontal and vertical distances between adjacent sinks are both 2 km; $n_t$ sensor nodes are deployed by mechanism and form a tree topology with the sink node on the water surface, and the monitoring information is efficiently transmitted to the surface for collection.

The parameters used in the simulation are set as follows:

TABLE II. Parameter Settings

| Parameter Names | Values |
|---|---|
| Volume of monitoring area（km） | 6×6×3 |
| Length of each cubic lattice（km） | 0.1 |
| Number of sink nodes | 9 |
| Perception radius of sink nodes（km） | 1.5 |
| Number of sensor nodes | $10\leq n_t\leq 150$ |
| Perception radius of sensor nodes（km） | $0.5\leq r\leq 1.0$ |
| Ratio of communication to perceived radius | $1.2\leq k\leq 2.0$ |

Figure 4 shows the network coverage simulation when $r$ is 0.8km and $k$ is 2. From the figure 4 we can see that when the number of nodes is less than 60, the DODA has a faster growth rate than other algorithms. When the number of nodes is 60, the coverage using DODA reaches 87.83%, which is a 18.13% improvement over the random deployment and a 11.87% improvement over the VBDA deployment. This is due to the fact that DODA ensures the connectivity under the case of sparse nodes and avoids the overlapping of the perceived areas effectively. With the increase of the nodes number, the growth rate of DODA gradually decreases. This is because the increase of nodes leads to more crowded among nodes and smaller space to adjust. When the nodes number is 150, the deployment using DODA reaches 96.21% coverage, which can meet the network requirements for the monitoring area effectively.

Figure 5 shows the network coverage simulation when the number of nodes is 100 and $k$ is 2. From the figure 5 we can see that due to the effective connectivity of nodes in the DODA, 38.31% coverage is achieved at a perception radius of 0.5 km. However, due to the nodes' perceived radius is too small, the sparse distribution of nodes reduces the connectivity performance of nodes, so the DASD and VBDA achieve 30.92% and 34.27% coverage. The DODA achieves 96.82% coverage when the perceived radius of nodes is 1km. As can be seen from the increasing trend of the coverage in the figure 5, the DODA has obvious advantages over other algorithms when the number of nodes is relatively scarce, and the coverage ratio is superior to other algorithms overall.

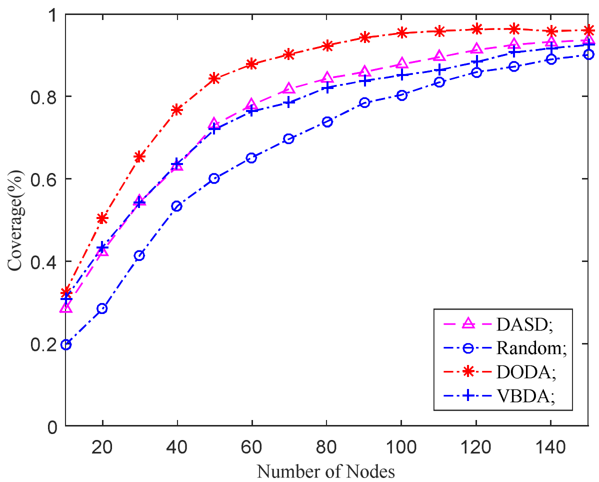


Fig. 4. Coverage with varying number of nodes

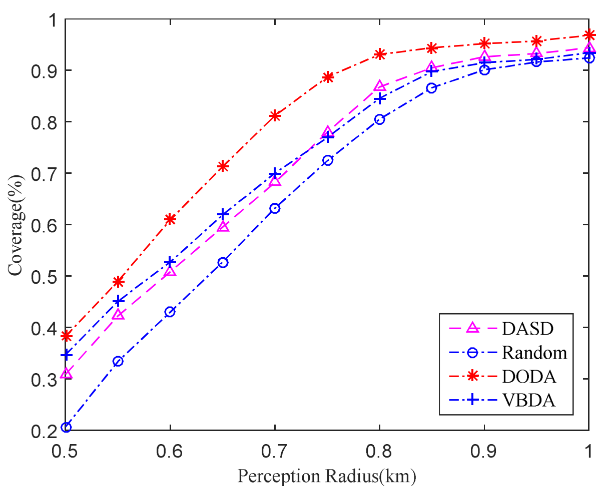


Fig. 5. Coverage with varying perceived radius

Figures 6 and 7 show the network coverage and connectivity simulation when the number of nodes is 80 and the perception radius of nodes is 0.8km. From Figure 7 we can see that the coverage characteristics of the DODA algorithm are relatively stable, the coverage is between 85.34% and 92.82%, the oscillation of it is small. This is because the DODA algorithm dynamically adjusts the distance between adjacent nodes based on $k$ to ensure the monitoring quality of the network. While the other three algorithms have a poor coverage performance when the communication perception is relatively low. The DASD algorithm achieves 28.33% coverage when k is 1.2. This is because it pursues to achieve less overlap among nodes. However, the smaller k means the closer the distance between two nodes should be. The coverage of node becomes meaningless when nodes cannot keep connectivity with neighbors. When the node perceived communication radius ratio is greater than 1.6, the coverage performance of DASD and VBDA tend to be stable. In this case, the DODA achieves 6.82% and 8.24% respectively over the coverage characteristics compared with DASD and VBDA.

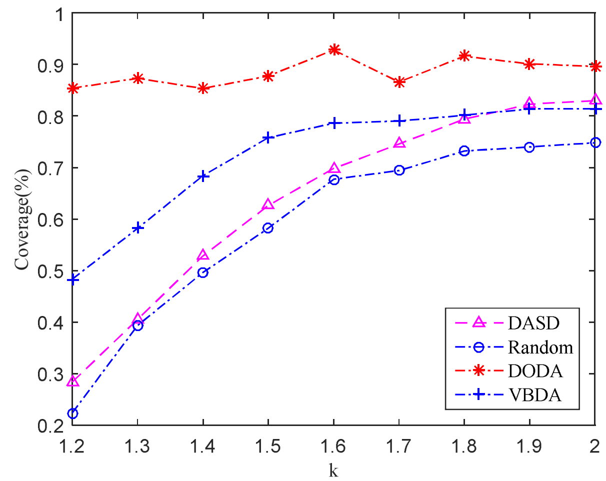


Fig. 6. Coverage with varying k

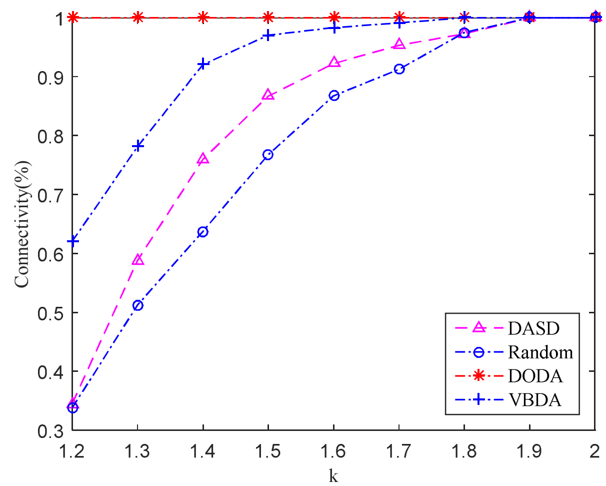


Fig. 7. Connectivity with varying k

From the above experimental results, we can see that because nodes are fully connected as premise of network coverage optimization in DODA, when $k$ changes, the node coverage can still be relatively stable, when the nodes are sparse, DODA has a faster growth rates in coverage than others several algorithms, and it always has a higher coverage with the same number of nodes.

## V. Conclusion

In this paper, we present a deployment optimization mechanism using depth adjustable nodes (DODA) to optimize the coverage and connectivity jointly in UASNs. The DODA is implemented in two phases. The first phase is to build trees by depth adjustment to ensure network connectivity. The second phase is to adjust the node using neighbors' location information to optimize the network coverage under the premise of keeping the network topology unchanged. The comparisons between DODA and three other node deployment algorithms demonstrate that DODA can achieve more than 6% optimization of the coverage while guarantee all sensor nodes connected in the UASNs.


## ACKNOWLEDGMENT

We thank the wireless and underwater communications laboratory of Tianjin University for helping this research.


## REFERENCES


[1] G. Brataas, A. Lie and T. A. Reinen, "Scalability analysis of underwater sensor networks," in Oceans, Bergen, Norway, 2013, pp. 1-9.

[2] A.A. Sheikh, E. Felemban, M. Felemban and S.B. Qaisar, "Challenges and opportunities for underwater sensor networks," in Innovations in Information Technology, Al-Ain, United Arab Emirates, 2016, pp.1-6.

[3] V. Bokser, C. Oberg, G. S. Sukhatme and A Requicha, "A small submarine robot for experiment in underwater sensor networks," Symposium on Intelligent Autonomous Vehicles, vol. 37, no. 8, pp. 239-244, July 2004.

[4] G. Tuna and V.C. Gungor, "A survey on deployment techniques, localization algorithms, and research challenges for underwater acoustic sensor networks," International Journal of Communication Systems, vol. 30, no. 3, pp.1-21, Apr 2017.

[5] D. Pompili, T. Melodia and I. F. Akyildiz, "Three-dimensional and two-dimensional deployment analysis for underwater acoustic sensor networks," Ad Hoc Networks, vol. 7, no. 4, pp. 778-790, June 2009.

[6] A. Almutairi, S. Mahfoudh, "Deployment Protocol for Underwater Wireless Sensors Network based on Virtual Force," International Journal of Advanced Computer Science & Applications, vol. 8, no. 11, pp. 241-249, Jan 2017.

[7] H.Z. Du, N. Xia and R. Zheng, "Particle swarm inspired underwater sensor self-deployment," Sensors, vol.14, no. 8, pp.15262-15281, Aug 2014.

[8] P. Jiang, Y. Feng and F. Wu. "Underwater Sensor Network Redeployment Algorithm Based on Wolf Search," Sensors, vol. 16, no. 10, pp. 1754, Oct 2016.

[9] A. Prakasan, M. Ovinis and M.Y. Javaid. "A Numerical Investigation of the Drag Forces on a Fleet of Underwater Gliders," Journal of Computational & Theoretical Nanoscience, vol.23, no. 2, pp. 1272-1276, Feb 2017.

[10] K. Akkaya and A. Newell, "Self-deployment of sensors for maximized coverage in underwater acoustic sensor networks," Computer Communications, vol. 32, no. 7-10, pp. 1233-1244, May 2009.

[11] J. Wu, Y. Wang and. L Liu. "A voronoi-based depth-adjustment scheme for underwater wireless sensor networks," Smart Sensing & Intelligent Systems, vol. 6, no. 1, pp. 244-258, Jan 2013.

[12] S. Williams, B. Brant, R. Eadie and S. Mclean, "A comparison of seafloor network topologies," in Oceans, Shanghai, China, 2016, pp. 1-4.

[13] L.M. Wolff, R. Diamant and L. Lampe, "Spatial dependencies between velocities of underwater drifting nodes," In ACM International Conference on Underwater Networks and Systems, New York, USA, 2012, pp.1-2.

[14] J. Liu, Z. Wang, J.H. Cui, S. Zhou and B. Bang, "A Joint Time Synchronization and Localization Design for Mobile Underwater Sensor Networks," IEEE Transactions on Mobile Computing, vol. 15, no. 1, pp. 530-543, Mar 2016.