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A VORONOI-BASED DEPTH-ADJUSTMENT SCHEME FOR UNDERWATER WIRELESS SENSOR NETWORKS

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Abstract- Underwater wireless sensor network (UWSN) is a special kind of wireless sensor network which is composed of a large quantity number of wireless sensor nodes deployed in the water. While there are extensive studies on deploy-issue of terrestrial wireless sensor networks (WSN), UWSN has not been paid enough attention due to the challenges of UWSN, such as low available bandwidth, highly varying multipath, and large propagation delays. In this paper, we propose a depth-adjustment scheme to maximize the coverage in 3D space. After deploying nodes in the water surface, we use Voronoi diagram to compute redundant nodes whose disappearance will not decrease the coverage in 2D space, and then we determine the depth that redundant nodes should be moved towards. After all the redundant nodes have moved to the lower layer, the algorithm continues to schedule redundant nodes of the lower layer until 3D space coverage is fulfilled.

Index terms*:* UWSN, Voronoi, 3D space, Sensor Deploying.

I. INTRODUCTION

Recently, UWSN has received considerable attention. These kind of sensing networks consist of a large number of underwater sensing nodes which can communicate with each other using acoustic signals or radio, and limited number of surface sinks which will collect data from underwater nodes. Different from terrestrial WSN sensor deploying problems, sensor deploying of UWSN has 3D requirement characteristics which introduce new challenges in terms with coverage, connectivity and mobility [1]. Coverage guarantees every spot of the region can be monitored in the UWSN, and connectivity guarantees the data can be transmitted so that nodes can relay their monitored data to on-shore station. Ref. [2] has investigated the problem of achieving maximal 3D coverage with the least number of sensors, and suggested the sensor deployment pattern that creates the Voronoi tessellation of truncated octahedral cells in 3D space. While a lot of research has been done for node deployment and self-organization in terrestrial WSN [3], there is still much to do for node deployment in UWSN [4].

Depth-adjustment system effectively resolves the problem of human intervention in node deploying [5][6][7]. However, factually the underwater environment is unknown or dangerous such as disaster area, toxic region or deep sea. In addition, most of the node deployment scheme requires a large number of underwater sensor nodes be placed in the pre-determined location, so human intervention brings about unnecessary spending-time and additional cost. With the advantage of depth-adjustment, coverage of the network in underwater circumstance will be enhanced autonomous [8]. But deploying a mass of nodes in order to achieve high coverage of given region without human intervention would make nodes gather in a high level density which would arouse problems such as coverage overlaps, redundant nodes, communication interference and energy waste. Thus, a purely random deployment sensing network without human intervention is not practical. Currently, Voronoi diagram is frequently used in WSN coverage optimization [9][10][11]. Ref. [11] introduced an approach of scheduling nodes based on the threshold value of Voronoi polygon area which every node is responsible for. In our proposed scheme, we use a similar idea to Ref. [11]. However, we do not set up a given area value as threshold.

In this paper, we propose a mechanism to maximize the coverage of the total monitored region with limited number of sensor nodes. We use Voronoi diagram to determine which sensor nodes in the same depth of the water are redundant node. To achieve maximum coverage of the 3D monitored region, we let redundant nodes sink to a certain depth, and then continue to use Voronoi diagram to determine the new group of redundant nodes in the new layer of the nodes. Algorithm will be stop until there is no room for nodes to be decent.

The organization of the paper is as follows. After a general introduction of the depth-adjustment scheme for UWSN, the description of our system model and assumption is presented to the section II. The scheme of depth-adjustment for underwater 3D space has been proposed in section III. In section IV, performance of our scheme is evaluated. The paper has been concluded in section V.

II. SYSTEM ILLUSTRATION AND DEFINITIONS

a. Problem Definitions

We propose the scheme attempt to maximize the total coverage of 3D underwater space while striving to minimize the total number of sensor nodes. Computational geometry is frequently used in WSN coverage optimization, the most commonly used approach are Voronoi diagram. In our proposed scheme, we also use Voronoi diagram. To determines if a node should adjust its depth, we employ the average area of all the Voronoi polygons that nodes in the same depth of the water are responsible for as the threshold. If the area of a Voronoi polygon is smaller than the average area of the total Voronoi polygons of the same depth, the node responsible for the Voronoi polygon should be list into the scheduling list.

b. System Model and Assumption

Our proposed architecture is depicted as Figure 1. Initially, sensor nodes are random uniformly spread on the surface of the ocean. In addition, a sink station should be deployed in the center of the surface as a management node of all sensor nodes. Then, The sink construct Voronoi polygons of sensor nodes based on received their location information. After computing the average area of Voronoi polygons, our algorithm compares each Voronoi polygons and lists the nodes whose responsible Voronoi polygon has a smaller area than the average value into the scheduling list. Our algorithm runs iteratively until sensor nodes reach the bottom of the ocean.

To achieve coverage in underwater circumstance, we assume that all these sensors have the ability to adjust their positions in vertical direction. In addition, each node knows its local position in the monitored region. In every round of the algorithm, nodes exchange their location information to their neighbours. Further, we use Sensing Range (R_S) and Transmitting Range (R_T) represents the range of sensing ability and communication ability, respectively.

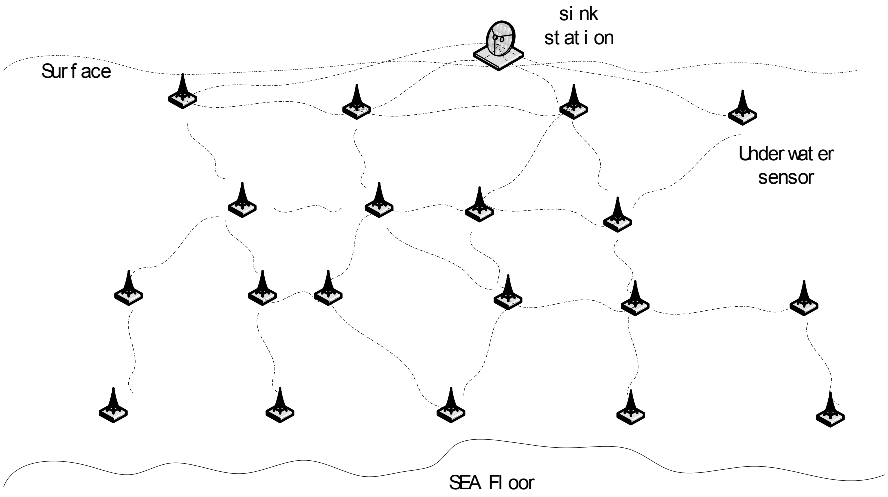

Figure 1. Underwater Sensor Deployment Architecture

c. Formal Definition of our work

1) Voronoi Diagram

Voronoi Diagram is an important structure in computational geometry. It represents the proximity information about a set of geometric nodes. The Voronoi diagram of a number of nodes divides the space into polygons. Every point in a given polygon is closer to the node in this polygon than to any other node. In a 2D region R^2, we define Voronoi polygon as $V(s_i) = \{x \in R^2 \| s_i - x | \leq | s_j - x |, i \neq j\}$ where s_i is the set of sensor nodes, which is illustrated in Figure 2.

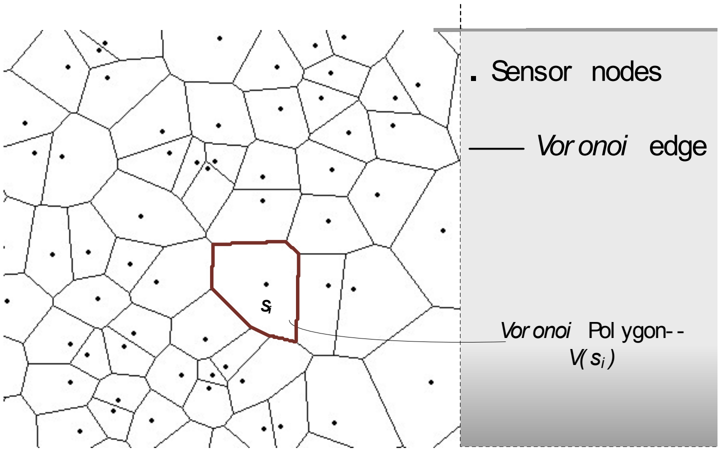

Figure 2. Voronoi Diagram

2) Scheduling Nodes

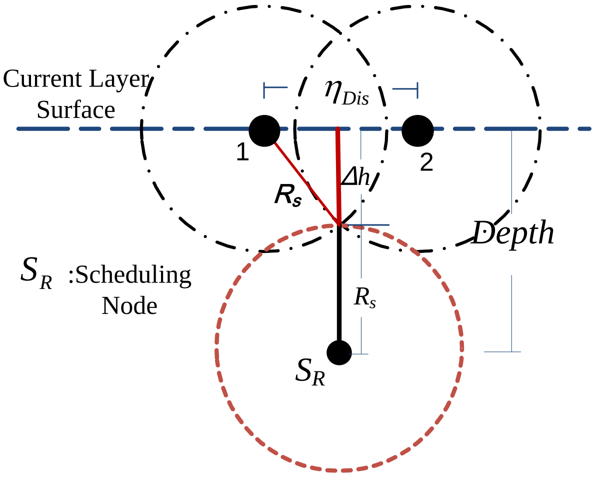

Figure 3. Presentation of Δh

Scheduling nodes are those nodes should adjust depth to a deeper layer. The determination of scheduling nodes can be illustrated as follows: Sum up all the areas of Voronoi polygons in the current layer of the water and calculate the Average area (η_{Area}) of the total Voronoi polygons with Equation (1).

$$\eta_{Area} = \frac{\sum_{i=1}^{N} A_i}{N} \tag{1}$$

Where A_i represents the area of Voronoi polygon $V(s_i)$, and N is the total number of nodes in the current layer. We call s_i as scheduling node if its responsible Voronoi polygon has a smaller area than the average value, e.t. $A_i < \eta_{Area}$.

3) Depth Adjusting

Depth that scheduling nodes should be adjust to is given by

$$Depth = \Delta h + R_s \qquad (2)$$

Where Δh represents the depth difference between the intersection of nodes coverage overlaps and the surface of the current layer of water. According to Figure 3,

$$\Delta h = \sqrt{R_S^2 - \left(\frac{\eta_{Dis}}{2}\right)^2} \qquad (3)$$

After the determination of all the scheduling nodes of the same layer, the algorithm compute the average distance (η_{Dis}) between every two nodes with Equation (4).

$$\eta_{Dis} = \frac{\sum_{i \neq j}^{N} d(i,j)}{k} \qquad (4)$$

$d(i,j)$ in Equation (4) is the distance between any two nodes s_i and s_j, and k is the number of nodes pairs. In a monitored field with N nodes, nodes pairs k could be decided by Equation (5).

$$k = \frac{N*(N-1)}{2} \qquad (5)$$

From Figure 3 we could see that the coverage overlaps among nodes are associated with the distance between nodes. When $\eta_{Dis} > R_S$, the gap between nodes would be much more bigger than what it is when $\eta_{Dis} < R_S$.As the distance η_{Dis} continues getting larger,Δh will reach to 0 when $\eta_{Dis} = 2R_S$. In the determination ofΔh, we defer to the MINIMIZE principle: Chose a smallerΔh would make the blind area that brought about by the nodes of upper layer be covered by nodes of lower layer. When$\Delta h = 0$, the blind area may be well-fixed by nodes in lower layer. In the other hand, when η_{Dis} reach a smaller value than R_s, dense nodes would bring about extensive coverage overlaps, as the distance infinitely close to 0, Δh infinitely close to R_S: $\lim_{\eta_{Dis}\to 0}\Delta h = R_S$. Since 0 is the ultimate value that η_{Dis} infinitely close to, the coverage blind area would still exist between layers if $\Delta h = R_S$, thus it cannot guarantee the coverage blind area be covered by lower layer. Since $\lim_{\eta_{Dis}\to R_S}\Delta h = \frac{\sqrt{3}}{2}R_S$, from the consideration of the MINIMIZE principle, $\Delta h = \frac{\sqrt{3}}{2}R_S$ would effectively minimize the blind area in the situation of $0<\eta_{Dis}<R_S$. We summarize the range of Δh spans correspondingly as follow:

$$\Delta h = \begin{cases} 0, & \eta_{Dis} \geq R_S \\ \frac{\sqrt{3}}{2}R_S, & 0<\eta_{Dis}<R_S \end{cases} \tag{6}$$

Therefore, according to Equation (2) and (6), the depth for adjusting will be

$$Depth = \begin{cases} R_S, & \eta_{Dis} \geq R_S \\ R_S + \frac{\sqrt{3}}{2}R_S, & 0<\eta_{Dis}<R_S \end{cases} \tag{7}$$

III. DEPTH-ADJUSTMENT FOR UNDERWATER 3D SPACE

Suppose nodes are spread randomly and uniformly in the surface of the monitored region with the sink station, the algorithm starts with 5 steps: 1) Discovering; 2) Area Calculating; 3) Scheduling nodes determination; 4) Depth adjusting; 5) Re-examination;

1) Discovering

This is the initial phase to construct Voronoi diagram of the network at the same depth. Firstly, nodes communicate with the sink to broadcast their position information with a hello packet, which contains node ID and planar coordinates. Then, the sink constructs the Voronoi diagram of the network based on nodes position information delivered by these hello packets.

2) Area Calculating

The sink calculates the area of each node's responsible Voronoi polygon and the average area in this phase. The area information is stored in the area information table.

3) Scheduling nodes determination

The sink searches in the table to determine which nodes are scheduling nodes.

4) Depth Adjusting

Scheduling nodes move to the certain depth based on the average area as we talked about last Section. It is worth notice that the sink will empty its area information table and saving memory space for continuous storing before the termination of this phase.

5) Re-examination

After nodes descending, the repetition of above phases will extend to a deeper level, the newly generated layer by nodes descending called "deeper layer". In this phase algorithm checks if there is still room for deeper expanding, if yes, the algorithm repeats on the deeper layer.

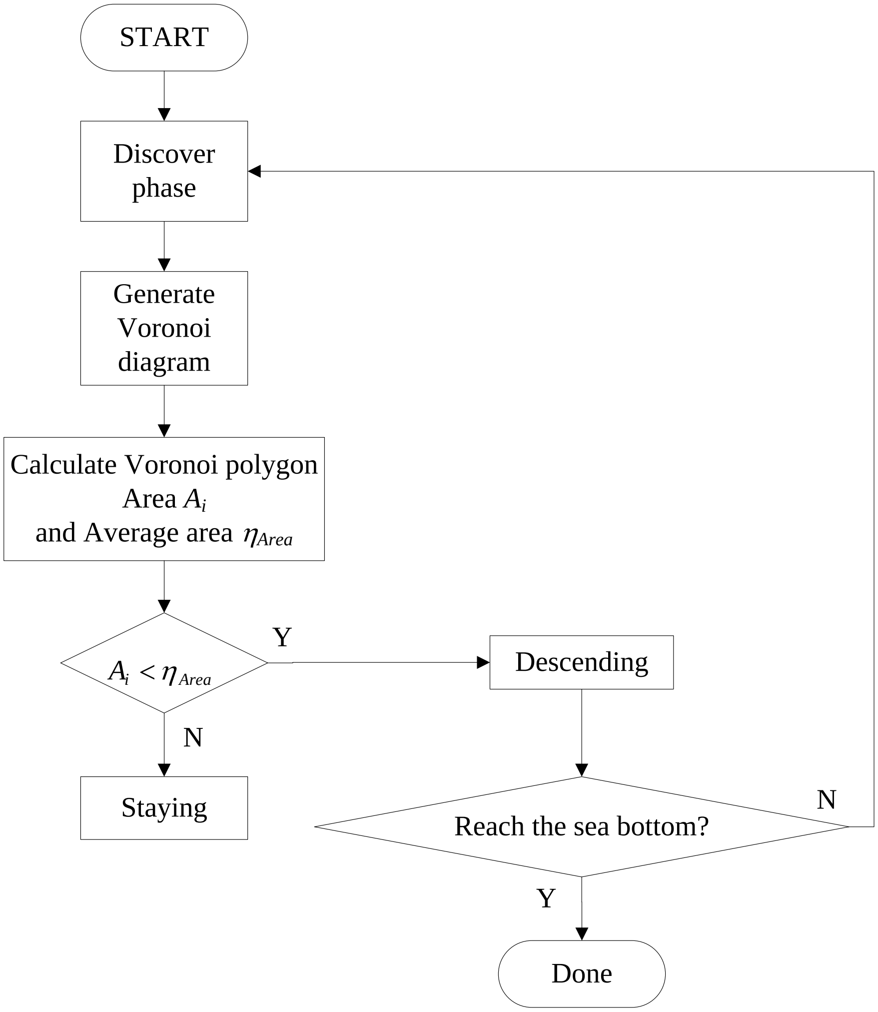

Figure 4. The flow of the algorithm

```
Input Nodes;
Initialize Nodes ID and Nodes Position;
while $MaxDepth \geq 0$
    Initialize Voronoi Diagram;
    for all nodes do
        calculate Voronoi_Area(ID);
    end for
    $\eta_{Dis} \leftarrow$ compute Average_Distance ( );
    if $\eta_{Dis} \geq R_S$ then
        $Depth \leftarrow R_S$;
    else
        $Depth \leftarrow (1+\sqrt{3}/2)\, R_S$;
    end if
    $\eta_{Area} \leftarrow$ calculate Average_Area();
    for all nodes do
        if Voroni_Area(ID)<Average_Area() then
            descending_List $\leftarrow$ Node(ID);
        end if
    end for
    for all nodes in descending_List do
        Descendto(Depth);
    end for
    $MaxDepth \leftarrow MaxDepth - Depth$;
end while
```

Figure 5. Pseudo-code of the algorithm

According to the steps above, the flow of the algorithm is depicted in Figure 4. In addition, we show the pseudo-code of the algorithm in Figure 5. At the beginning of the algorithm, nodes transfer their *ID* and locations to the sink. Base on this information, the sink generates the

Voronoi Diagram, and calculate each node's relevant Voronoi polygon area in Line 4-7. Line 8-13 determines the depth that scheduling nodes should descend to. After comparing the average area and node's Voronoi polygon area in Line14-19, scheduling nodes are determined. Then, the scheduling nodes are descended to deeper layer in Line 20-22. Algorithm circulates until nodes reach the bottom of the sea.

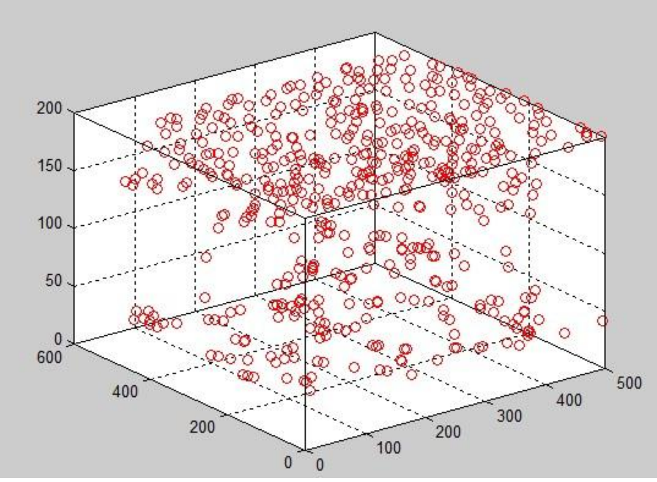

Figure 6. The final topology after the algorithm

Figure 6 shows the final topology of the algorithm with 500 nodes are deployed randomly in a 500m×500m×200m 3D region. We can see that after the execution of the algorithm, nodes are distributed not only in the surface of the water but the entire region of the water as we expected.

IV. PERFORMANCE EVALUATION

a. Settings

In this section we present the results obtained from the simulation and discuss their implications. The simulations were realized by Matlab. Here, we consider the coverage of the whole region and the connectivity between nodes as the main criterions of our network.

We start our simulation with varying numbers of nodes uniformly deployed in a given space of 500m×500m×200m. We use the average value as our final results. Besides, we assume that there were no errors occur in transmitting message phases and in nodes-descending process.

b. Coverage

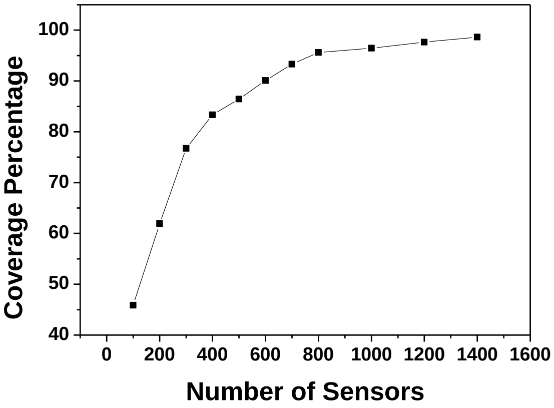

Figure 7(a). *Sensor Number* vs *Coverage*

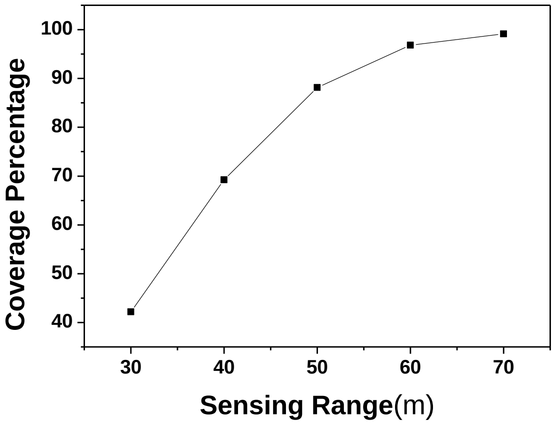

Figure 7(b). R_S vs *Coverage*

Obtaining an optimistic coverage in a given 3D region is the fundamental purpose of our scheme. Figure 7(a) shows that coverage of the target space varying with different number of nodes. The coverage achieves 98.622% with 1400 sensor nodes while the sensing range of each node is 50m. With the increase of sensors, it is obviously that there exist a sharp increase of coverage when number of nodes varying between 100-400, meanwhile the whole coverage stays nearly still with nodes over 800. This suggests that 800 sensors are sufficient to cover the desire region under the sensing range of 50m.

In Figure 7(b), the coverage of the network with varying sensing range is depicted. We access the coverage using different sensing range, and we set the number of nodes as 500. As expect, the coverage has a distinguished improvement when the sensing range R_S increases. Under the sensing range of 70m, the network coverage reaches 99.15%.

c. Connectivity

Connectivity of nodes is crucial for transmitting messages as well. To guarantee the message can be transfer effectively to the sink, we define the connectivity of the network with the percentage of nodes that can reach the surface sink. We used the following metrics to observe the connectivity performance:

Total number of nodes: total number of sensors that deployed in the 3D space;

R_{sink}: Transmitting Range of the surface sink;

$R_T/R_S(r)$: ratio of Transmitting Range to Sensing Range of the sensor;

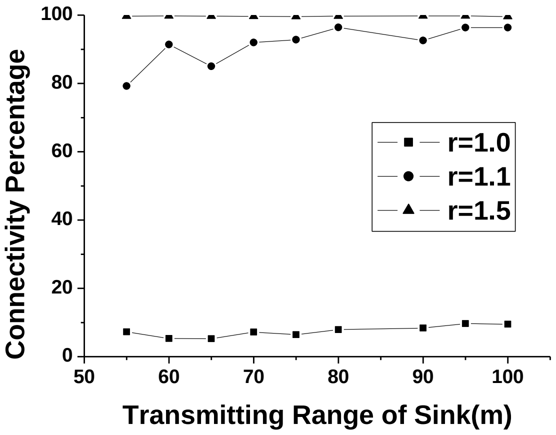

Figure 8.(a) R_{sink} vs *Connectivity*

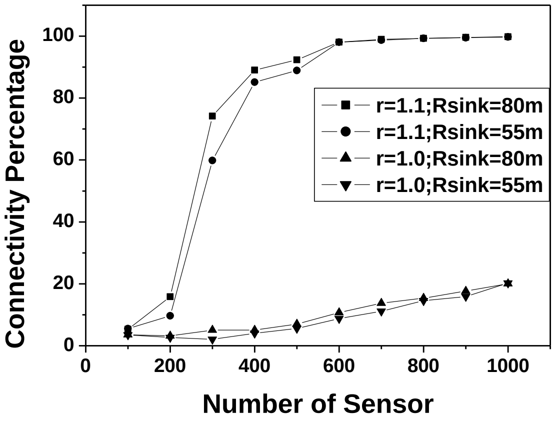

Figure 8.(b) *Sensor Number* vs *Connectivity*

Figure 8(a) represents the relation between R_{sink} and r. In this experiment we set total number of nodes=500. It is obviously that connectivity of the network has a wide difference between r=1.0 and r=1.1. At the meantime, as R_{sink} getting larger, connectivity has a gentle increase. Since nodes can communicate with each other through multi-hops, it is easier for sensor to transmit data to the surface sink as their Transmitting Range getting larger. The results shown in Figure 8(a) indicate that the capability of the sink has little influence on network connectivity though the connectivity of our approach is defined by the percentage of nodes that can reach the sink. After nodes descend to a certain depth beyond sink transmission ability, data transmission mainly depends on multi-hops between nodes.

Figure 8(b) shows connectivity with various *node number*, r and R_{sink}. As what we have learned from Figure 8(a) that R_{sink} has little influence on connectivity, we can see from Figure 8(b) that there are little changes in connectivity when R_{sink} change under the same number of nodes and the same r. Besides, when the sensor number grows, relevant connectivity grows slowly. On the other side, however, connectivity has a sharp increase when r>1.0. Note that nodes are randomly deployed in the water, the distance between nodes can not be assure. As r grows, the transmitting capability strengthens accordingly. Therefore, nodes can transmit data to longer neighbors under a certain sensing range. That leads to connectivity improvement.

V. CONCLUSIONS

In this paper, we introduce a distributed approach for under water 3D circumstance. The proposed approach aimed at covering an underwater space with less human intervention. Although sensor nodes are randomly deploy in the surface of the water and can not move in horizontal direction, with the help of depth adjustment technique, sensors can be lower to any depth so that the coverage of underwater circumstance could be insure. The depth adjustment is done based on the density of sensors, we use Voronoi approach to calculate the density to decide which nodes should be descend down to a deeper layer. Experiment turn out that our approach has a good performance in network coverage and connectivity. However, the experiments also point out that connectivity of the network is very sensitive to R_T/R_S. From Fig. 13 and Fig. 14, we learn that R_T/R_S play a key role in network connectivity. Besides, there still exist some limitations to be considered such as network lifetime and data transmission efficiency, which should be done in our future work.

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