Utilizing Automatic Underwater Vehicles to Prolong the Lifetime of Underwater Sensor Networks

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***Abstract*—Consisting of sensors and vehicles, UnderWater Sensor Networks (UWSNs) are deployed to perform collaborative monitoring tasks over a given region. UWSNs could be utilized in the regions of water quality monitoring, mining equipment monitoring, oceanographic data collection, pollution surveillance, etc. However, comparing with terrestrial wireless sensor networks, it is more crucial to prolong network lifetime for UWSNs since the varying characteristics of the underwater environment and superior difficulty of underwater device maintenance. In this paper we present a three-dimensional hemisphere model for UWSNs and prove that the improvement in network lifetime by utilizing one Automatic Underwater Vehicle (AUV) is upper bounded by a factor of eight in 3D UWSNs. In addition, the AUV only needs to stay within a two hop radius of the sink. We further propose an underwater aggregation routing algorithm UARA to prolong lifetime by utilizing one AUV for UWSNs. Finally, we perform extensive simulations to validate our conclusions.**

Keywords: underwater sensor networks, automatic underwater vehicle, network lifetime

I. INTRODUCTION

The Earth is a water planet. The largely unexplored vastness of the ocean covers about two-thirds of the surface of the Earth. Recently, there has been a growing interest in monitoring aqueous environments, resource exploitation, national security and defense in oceans, etc. Consisting of sensors deployed underwater and networked via acoustic links, UWSNs enable applications for water quality monitoring, mining equipment monitoring, oceanographic data collection, pollution surveillance and so on. The network architecture of underwater sensor networks can be classified into three types, namely, Static Two-dimensional Underwater Sensor Networks, Static Three-dimensional Underwater Sensor Networks and Sensor Networks with AUVs [1][2]. The 2D underwater sensor networks consist of sensor nodes anchored to the bottom of the ocean or shallow waters, while the 3D underwater sensor networks are used to detect and observe ocean phenomena that cannot be absolutely observed by means of ocean bottom sensor nodes, e.g., to sample or monitor the 3D ocean environment. In 3D underwater sensor networks, sensors are deployed and float at different depths to observe a given phenomena. For this purpose, it is liable to anchor winch-based sensor devices to the bottom of the ocean rather than attach each sensor node to a surface buoy which might obstruct ships or may be easily detected and destroyed by enemies in military settings [3]. In addition, AUVs, equipped with underwater sensing and communication devices, can function without tethers, cables, or remote control, and therefore they have a multitude of applications in oceanography, environmental monitoring, and underwater resource studies. Furthermore, AUVs can be used to enhance the capabilities of underwater sensor networks in many ways, e.g. adaptive sampling [4] and self-configuration. However, the integration and enhancement of UWSNs with AUVs is an almost unexplored research area [5].

In UWSNs, acoustic communications are the typical physical layer technology which are very different from terrestrial radio propagation, such as limited bandwidth, the acoustic signal's bandwidth-distance relationship [6] and high propagation delay. Research in networking protocols for underwater sensor networks is a very young field. There exist only a small amount of work providing routing algorithms for underwater sensor networks [3], [7], [8], mostly underlining how to design network protocols to adapt and utilize the characteristics of acoustic communication. However, they neglect a very stern problem—how to prolong the network lifetime in UWSNs. Underwater sensors only have limited battery power and usually their batteries cannot be recharged, also because solar energy cannot be exploited. Therefore, the network lifetime is a very important factor to measure the performance of UWSNs, especially in 3D UWSNs whose network lifetime are decreasing more seriously than terrestrial wireless sensor networks or 2D UWSNs while the network range is growing. To solve this problem, deploying more underwater sensors in hot spots will be testified to be an impractical approach because underwater sensors are more expensive than terrestrial motes [9] and dense deployed sensors could be easily detected and destroyed by enemies and ships. Therefore, we propose an underwater aggregation routing algorithm UARA to prolong the network lifetime by using one AUV in UWSNs.

We first present a three-dimensional hemisphere model for UWSNs and prove that the improvement in network lifetime by utilizing one AUV is upper bounded by a factor of eight in dense and large UWSNs. Meanwhile, the AUV only need to stay in two hops from the sink. We then prove that in dense and large UWSNs, the improvement in network lifetime brought by our proposed UARA is close to the upper bound. Furthermore, we implement UARA in sparse UWSNs and propose an AUV Mobile Scheme AUVMS for the AUV to reduce its energy consumption. Our simulations show that the lifetime improvement by utilizing UARA is at least 300% in sparse UWSNs.

The remainder of the paper is organized as follows. Section II summarizes related work. Section III describes network architecture and proposes a three-dimensional hemisphere model for UWSNs. Section IV presents UARA and analyzes its performance in dense and large UWSNs. Section V describes the implementation of UARA in sparse underwater networks. Section VI gives the simulation results in sparse underwater sensor networks. Finally, Section VII concludes the paper.

II. RELATED WORK

Some recent papers propose network layer protocols specifically tailored for underwater acoustic networks. In [3], two distributed routing algorithms are introduced for delay-insensitive and delay-sensitive applications. In [8], an energy-efficient routing protocol is designed based on the insights gained in analysis from acoustic communications. In [7], a robust, scalable and energy-efficient routing algorithm, called vector-based forwarding (VBF) is presented. However, these papers neglect considering network lifetime prolongation, one of the most important performance metrics in underwater sensor networks.

Previous experimental work has shown the feasibility of relatively inexpensive AUV submarines equipped with multiple underwater sensors that can reach any depth in the ocean [9]. Hence, they can be used to enhance the capacities of underwater sensor network in many ways. In [4], the authors apply AUVs in adaptive sampling in the ocean. In [10], one AUV has been used as a data mule to relay information between disconnected sensor clusters. In addition, others also utilize AUVs in underwater localization [11]. However, our approach is different from former papers. To the best of our knowledge, we are the first one to utilize AUVs to improve lifetime in underwater sensor networks.

There has been intensive study in network lifetime prolongation for terrestrial wireless sensor networks in last few years. In [12], the authors exploit sink mobility for maximizing sensor networks lifetime and give a linear programming formulation for the joint problems of determining the movement of the sink and the sojourn time at different points in the network that induce the maximum network lifetime. In [13], a joint mobility and routing strategy is proposed to improve lifetime by taking both base station mobility and multi-hop routing into account. In [14], the authors investigate the performance of a large dense network with one mobile relay and show that improvement in network lifetime over an all static network is upper bounded by a factor of four. Also, the proof implies that the mobile relay needs to stay only within a two hop radius of the sink. Meanwhile, they propose a joint mobility and routing algorithm which comes close to the upper bound. Since sink mobility is usually limited in underwater sensor networks, we do not consider improving lifetime by sink mobility. We extend [14] to 3D UWSNs by using an AUV as a mobile relay and propose an underwater aggregation routing algorithm UARA especially for 3D UWSNs.

III. NETWORK ARCHITECTURE

In this section, we consider a network architecture for 3D UWSNs which can be used to detect and observe phenomena that cannot be adequately observed by means of ocean bottom or surface sensor nodes, i.e., to sample the 3D ocean environment. In a 3D UWSN, sensor nodes need to be deployed in their responsible area to observe a given phenomenon. To maintain their locations within such an area, one possible solution is to anchor winch-based sensor devices to the bottom of the ocean [3], while another approach is to let sensor nodes have weak mobility to maintain their location. Since acoustic communication range is much larger than sensing range (e.g., the transmission range of the WHOI micro modem can achieve at distances up to 4 km [9]), in an underwater communication view, we can assume these nodes are *static*. In contrast, AUVs can travel to any area with strong mobility.

A. Network Model

In this section, we describe our underwater network models and basic assumptions. We assure that sensors are randomly deployed with high density ρ in a hemisphere area of radius $R \gg 1$. [1] By high density we means that in each hop the packet can travel as far as the transmission range in any direction. We assume that there are N sensor nodes in the network with one sink (surface station) n_0 at the center of the hemisphere underwater area. We define that network lifetime as the time till the first node dies because of energy depletion.

we assume a data logging application where the underwater sensors are required to send their sensing data at certain rate. Without loss of generality, we assume that the packet generation rate for the sensors is one. We assume the transmission range of all the sensors is equal to 1 and the sensors do not change their transmission powers. In addition, we assume that all sensor nodes have the same initial energy E and the energy of the sink is unlimited. For the sake of simplicity, we suppose the network has adopted optimal sleep scheduling protocols (The sleep scheduling methods are out of the scope of this paper). So the energy consumption in idle state can be ignored and we only consider the energy used in sensing, receiving and transmission. Since the transmit energy cost will be much larger than receive and sensing cost in acoustic communications (e.g., in the WHOI micro modem [9], the maximum transmit power is 50 W while the receive power is only 120 mW). To further simplify our energy model, we assume that the transmission energy dominates the total energy consumption, so that the difference between sensing and receiving energy consumption can be ignored. In our model, we assume the total energy consumption by sending out one packet is a constant e.

[1] The density of one area might be a function of location of nodes, requirements of underwater applications and so on, which is not the focus of the present work.

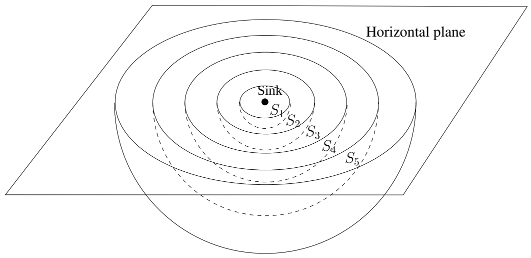


Fig. 1. Underwater hemisphere network model

To facilitate our analysis, we divide underwater sensors to different sets according to their transmit hops to the sink. The set S_i contains all the nodes which can reach the sink with minimal hop count i. For example, all the neighboring nodes of sink will be S_1. In a dense network, the sensor node n will be in the set S_k iff $k-1 < d(n, n_0) \leq k$, where $d(n, n_0)$ is the Euclidean distance between node n and the sink n_0. Thus, the nodes in S_i will be in the i^{th} hemisphere shell around the sink as showed in Fig. 1. We denote the nodes outside of all the transmission range of the sink as $\overline{S_1}$. The set of all the nodes which can reach the sink within j hops is denoted as $H_j = \bigcup_{k \leq j} S_k$.

B. Upper Bounds on Lifetime

In a hemisphere network, it is obvious that the nodes in S_1 will be the hot spots of the network because besides sending their own packets, they must relay other packets from the nodes in $\overline{S_1}$. Theorem 1 gives the lifetime upper bound for the hemisphere network.

Theorem 1: The lifetime of a static underwater network is upper bounded by $\frac{E}{R^3 e}$ time units.

Proof: Since the density of nodes in the hemisphere network is ρ, there would be $\frac{2}{3}\pi\rho$ nodes in S_1. Then the total initial energy stored in S_1 would be $\frac{2}{3}\pi\rho E$. Suppose the lifetime of the network is $\widetilde{T}$. In each time unit, there would be $\frac{2}{3}\pi\rho R^3$ packets generated by all the sensors in the network and each of them should be delivered to the sink. Since the sink can only received packets from the nodes in S_1, both the packets generated by nodes in S_1 and in $\overline{S_1}$ must be relayed by the nodes in S_1 at least once. Thus, the total energy stored in nodes in S_1 should satisfy:

$$\frac{2}{3}\pi\rho E \geq \widetilde{T} \times \frac{2}{3}\pi\rho R^3 \times e \tag{1}$$

The lifetime of the network $\widetilde{T}$ will be upper bounded by

$$\widetilde{T} \leq \frac{E}{R^3 e} \tag{2}$$

■

Similarly, Literature [14] prove that the network lifetime will be upper bounded by $\frac{E}{R^2 e}$ in a 2D terrestrial wireless sensor network with node density ρ and radius R. Thus, while the radius R are becoming larger, the lifetime of 3D UWSNs are declining more drastically than 2D terrestrial wireless sensor networks. Therefore, elongating the lifetime is extraordinary crucial in 3D UWSNs. We now prove that the lifetime upper bound can be improved by a factor of eight by using one AUV.

Theorem 2: The lifetime of an underwater hemisphere network is upper bounded by $\frac{8E}{R^3 e}$ time units by using one AUV.

Proof: The amount of traffic through nodes in H_i is at least the sum of the traffic generated in $\overline{H_i}$, which is $N - \frac{2}{3}\pi\rho i^3$. Obviously, the AUV has a transmission range of one and it can only be at one place at a time. Therefore, when using one AUV as a relay, packets generated in $\overline{H_i}$ should be relayed for at least $i-1$ hops by static nodes in H_i. Since the number of nodes in H_i is $\frac{2}{3}\pi\rho i^3$, we can bound the lifetime of the network by

$$\begin{aligned} T &\leq \frac{\frac{2}{3}\pi\rho i^3 E}{(N - \frac{2}{3}\pi\rho i^3) \times (i-1)e} \\ &= \min_i \frac{i^3 E}{(R^3 - i^3) \times (i-1)e} \end{aligned} \tag{3}$$

From inequality (3), we can conclude that when $i \geq 2$, as i increase, the upper bound will monotonically increase and when $i = 1$, the upper bound is infinity. Hence, the least upper bound on lifetime is when $i = 2$ and

$$T \leq \frac{8E}{(R^3 - 8)e} \tag{4}$$

In inequality (4), we have only considered the traffic generated in $\overline{H_2}$. For further analysis, we should take into account the traffic generated by H_2 too, which also need to pass through nodes in H_2 at least once. Thus, we can further tighten the bound to $\frac{8E}{R^3 e}$. ■

From Theorem 2, we can conclude that the AUV just needs to stay only within a two hop radius of the sink in order to maximize the lifetime, which is available and feasible for AUVs even in the harsh underwater environment. However, if we want to achieve the same upper bound by deploying more static nodes as relays, the cost will be very high.

Theorem 3: In order to prolong the lifetime to $\frac{8E}{R^3 e}$ time units, the number of static relay nodes we need to deploy are lower bound by $\frac{16}{3}\pi\rho(1 - \frac{1}{R^3})$.

Proof: Assume that the lifetime of nodes in H_i is larger than $\frac{8E}{R^3 e}$, then we have

$$\begin{aligned} \frac{2}{3}\pi\rho E(i^3 - (i-1)^3) \geq \frac{8E}{R^3 e} \times (R^3 - (i-1)^3)) \times e \\ i^3 - (1 + \frac{8}{R^3})(i-1)^3 \geq 8 \end{aligned} \tag{5}$$

When $i \leq 2$ the left side of inequality (5) will be less than 8. Therefore, we must at least deploy static relay nodes in H_2 to prolong the lifetime to $\frac{8E}{R^3 e}$. We denote that N_{S_i} is the number of static nodes in S_i, ${N_{S_i}}'$ is the number of static relays which should be deployed in S_i and $N_{\overline{H_i}}$ is the number of static nodes in $\overline{H_i}$. They should satisfy that

$$({N_{S_i}}' + N_{S_i}) \times E \geq (N_{S_i} + N_{\overline{H_i}}) \times \frac{8E}{R^3 e}$$
$${N_{S_i}}' \geq \frac{2}{3}\pi\rho(\frac{8}{R^3}(R^3 - (i-1)^3) - i^3 + (i-1)^3) \quad (6)$$

Thus, the number of static relay nodes N' is lower bound by

$$N' \geq {N_{S_1}}' + {N_{S_2}}' \geq \frac{16}{3}\pi\rho(1 - \frac{1}{R^3}) \quad (7)$$

■

From Theorem 3, we can conclude that using one AUV is a more efficient and economical approach to improve network lifetime in UWSNs, e.g., in a 3D underwater network with 200 static nodes and $R = 4$, we need deploy at least 37 static nodes to prolong the lifetime to $\frac{8E}{R^3 e}$. In contrast, we can achieve the same effect by using one AUV.

IV. UNDERWATER AGGREGATION ROUTING ALGORITHM

In this section, we introduce two different ways to prolong lifetime in UWSNs by using one AUV. Then, we present an Underwater Aggregation Routing Algorithm (UARA) and prove that it can prolong lifetime to $\frac{8E}{R^3 e} - \frac{64E}{R^6 e}$ time units in dense and large UWSNs.

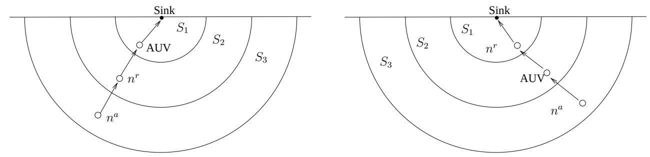
A. Static Routing

In this approach, the AUV decides a schedule, which is denoted by a sequence $\{(l_1, u_1), (l_2, u_2), \ldots, (l_N, u_N)\}$, where l_i is the 3D location of node i in the network, u_i is the duration when the AUV is at the location l_i, and N is the number of nodes in the network. When the AUV reaches at the location l_i, it will take the responsibilities of node i and allows node i to sleep in the duration u_i. *Static routing* means that the routes from a node to the sink will not be influenced by the current location of the AUV. In practice, one AUV can only stay at one place at a time, so the sum of the duration cannot exceed the lifetime of the network. It is clear that the optimal schedule is sorting the lifetime of all nodes in increasing order in every time unit, then using the AUV to help the first node in this order.

B. Dynamic Routing

In dynamic routing, the routes from a node to the sink will depend on the position of the AUV. In other words, sensors should know the current position of the AUV. In general, more packets are relayed by the AUV, more performance gain will be achieved from it.

For the network with one AUV and N static nodes, the optimal schedule of the AUV can be calculated through linear optimization in a way similar to [15]. The linear optimization model below determines the duration time t_k of the AUV at each node $k \in N$ so that the network lifetime is maximized. If the optimal value for a t_k is 0, the AUV does not visit node k. Every node $k \in N$ whose optimal t_k is positive is visited by the AUV for a time duration equal to t_k. Then the linear optimization problem can be formulated as follows:



(a) AUV in S_1 (b) AUV in S_2

Fig. 2. Aggregation line in H_3

$$Maximize \sum_{k \in N} t_k \quad (8)$$
$$s.t. \quad \sum_{k \in N} c_i^k t_k \leq E, \; i \in N \quad (9)$$
$$t_k \geq 0, \; k \in N. \quad (10)$$

where c_i^k is the sum of energy consumption of node i when the AUV is at the location of node k. Constraint (9) simply states that the energy consumed at each node i should not exceed the initial energy of that node. Constraint (10) assures the non-negativity of duration time t_k. Linear programming could get an optimal schedule of the AUV, but it's very hard to calculate c_i^k for dynamic routings. So we propose a feasible approach UARA to utilize one AUV.

C. Algorithm Description and Analysis For Dense Networks

A broad outline of UARA is as follows. The AUV starts from the sink, relays data with every nodes in H_2 together for $\frac{E}{Ne}(1 - \frac{8}{R^3})$ time units each and finally returns back to the sink so that it could be recycled at last. Assume that M is the current location of the AUV, then all traffic in $\overline{H_2}$ is first aggregated to points on the line OM, where O is the position of the sink. After reaching the aggregation line, the traffic is then directed hop by hop along the line OM until it reaches the sink.

As presented in Fig. 2, when the AUV travels to S_1, it should relay data from a node n^r in S_2; similarly, when the AUV travels to S_2, it should relay traffic from aggregation node n^a in S_3 to n^r in S_1. Since there are $\frac{16}{3}\pi\rho$ nodes in H_2, it is easy to prove that there exists $\frac{16}{3}\pi\rho$ independent aggregation lines from S_3 to the sink ,i.e., every node in H_2 will be used as n^r once and n^a in every aggregation line are different. And every aggregation line will maintain for $\frac{E}{Ne}(1 - \frac{8}{R^3})$ time units.

We outline the algorithm as follows:

1) Nodes in H_3
   The data generated in H_3 will be delivered as follows: The data generated by nodes in S_1 will be directly sent to the sink. Nodes in S_2 and S_3 will both send their data to nodes in $S_3 \backslash A$, which is the set of spare nodes which are not used as aggregation nodes in S_3. Nodes in $S_3 \backslash A$ will be responsible for relaying all the received data to the current aggregation node n^a.

2) Nodes in $\overline{H_3}$
The nodes in $\overline{H_3}$ will first relay the packets they generated to the line OM. For example, a node in $S_k, k > 3$ sends its data to a node on the line OM which is also in S_k, by relaying the data only via nodes in S_k. Then the packets will be delivered through the nodes in OM and reach the current aggregation node n^a. Finally, n^a will send the packets to the sink by the help of the AUV and one node n^r in H_2.

Theorem 4: In a dense network, UARA can extend the network lifetime to at least $\frac{8E}{R^3 e} - \frac{64E}{R^6 e}$, when the network radius $R > 4\pi + \frac{1}{8}$.

Proof: We can separate the network into three parts: H_2, S_3 and S_k with $k \geq 4$. We prove that under the algorithm all the network lifetime of the three parts is at least $\frac{8E}{R^3 e} - \frac{64E}{R^6 e}$.

a) Lifetime for nodes in H_2: A node in S_1 delivers its own data to the sink and relays traffic for nodes in $\overline{H_1}$. Since every node in S_1 will cost at most $\frac{E}{Ne}(1-\frac{8}{R^3}) \times N \times e$ units of energy for relaying data from the AUV, it can reserve $E' = \frac{8E}{R^3}$ units of energy for delivering its own traffic. Therefore, the lifetime of the nodes in S_1 is at least $\frac{8E}{R^3 e} - \frac{64E}{R^6 e}$. Similarly, since nodes in S_2 transmit their own data to a node in $S_3 \backslash A$ and we have reserved $E' = \frac{8E}{R^3}$ units of energy for this, they can also live for at least $\frac{8E}{R^3 e} - \frac{64E}{R^6 e}$.

b) Lifetime for nodes in S_3: The proof of the lifetime in S_3 is outlined in Appendix A.

c) Lifetime for nodes in S_k with $k \geq 4$: The proof of the lifetime in S_k with $k \geq 4$ is outlined in Appendix B. ■

Theorem 4 shows that UARA can achieve the lifetime of $\frac{8E}{R^3 e} - \frac{64E}{R^6 e}$. Since R^6 decays much faster than R^3, as the network radius R becomes large, the lifetime will approach 8 times that of the hemisphere network with one AUV.

V. DESIGN FOR SPARSE UNDERWATER NETWORKS

In Section IV, we have proved that in a dense and large underwater network, UARA could improve the lifetime by $\frac{8E}{R^3 e} - \frac{64E}{R^6 e}$. In this section, we will discuss how to utilize UARA in sparse underwater network.

A. Initialization

In sparse networks, greedy forwarding routing algorithms may not find the route. So we use GPSR [16] as the basic multi-hop routing in underwater networks. When a packet reaches a region where greedy forwarding is impossible, GPSR can recovers by routing around the perimeter of the region. In the initialization of UARA in sparse underwater network, the sink should know the geographical information of all the nodes in H_2 and all the nodes should know their hop distance from the sink. By GPSR, nodes can easily get their hop distance from the sink and neighbor information through beacon changes. Then every node in S_2 should send a triple $Tr\{n_1, n_2, A\}$ to the sink so that the sink can get essential information to establish the AUV's itinerary. In every triple Tr, n_2 is the geographical information of the sender, n_1 is the location of the relay node from the sender to the sink, and A is a set of neighbor nodes of the sender in S_3.

```
Input: T: the minimum spanning tree
root: the root node of T
k: the index of I
Output: I: the itinerary of the AUV
if has_son(T,root) then
    n = first_son(T,root);
    if Selected[n]==0 then
        I[++k]=n;
        Selected[n]=1;
    end
    k = APPROX-TSP-TOUR(T,n,I,k);
    m = neighbor_son(T,root,n);
    while m!=-1 do
        if Selected[m]==0 then
            I[++k]=m;
            Selected[m]=1;
        end
        k = APPROX-TSP-TOUR(T,m,I,k);
        m = neighbor_son(T,root,m);
    end
end
return k;
```

Algorithm 1: APPROX-TSP-TOUR

B. AUV Mobile Scheme

Based on all the triples from nodes in S_2, we propose an AUV mobile scheme AUVMS to set up an itinerary of the AUV guiding the AUV which starts at the sink, visits all the nodes in S_1 and N_1 selected nodes in S_2 and finally returns back to the sink (N_1 is the number of nodes in S_1). Though we ignore the energy consumption for transmission of the AUV, the energy cost for underwater traveling can not be negligible since the mobile energy cost dominates the total energy consumption for the AUV. Therefore we try to find the shortest path for the AUV's traveling to minimize energy consumption of the AUV. Meanwhile, the traveling time between two nodes will reduce too. We can formulate it to the traveling-salesman problem (TSP) with the triangle inequality [17]. Since it is NP-complete, we are unlikely to find a polynomial-time algorithm for solving it exactly. But even so, firstly, if N_1 is small, an algorithm with exponential running time may be perfectly satisfactory. Secondly, we can implement a near-optimal solution APPROX-TSP-TOUR in polynomial time. In order to implement APPROX-TSP-TOUR, we first select N_1 nodes from S_2 which are nearer the central axle line, and then establish a minimum spanning tree T grown from root vertex n_0 by MST-PRIM [17] for all the nodes in S_1 and the selected nodes in N_1. Finally, we use APPROX-TSP-TOUR$(T, n_0, I, 0)$ to get the itinerary I for the AUV. And for $\forall i, 1 \leq i \leq N_1 + N_2$, if $I(i) \in S_1$, all the neighbor nodes of $I(i)$ which have not been selected as relay nodes before,

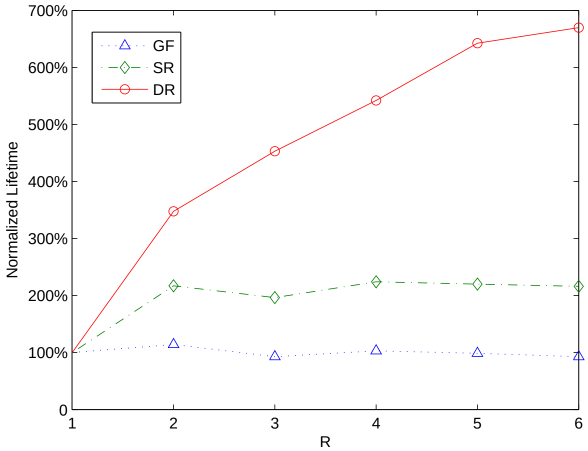


Fig. 3. The Network lifetime for 3D grid underwater hemisphere networks

should be relay nodes one by one when the AUV travels at $I(i)$. Therefore, the sojourn time at $I(i)$ equals to $\frac{EN_r}{Ne}(1-\frac{8}{R^3})$ time units, here N_r is the number of available relay nodes of $I(i)$; if $I(i) \in S_2$, we can find current relay node from $Tr(i)$ and the sojourn time is $\frac{E}{Ne}(1-\frac{8}{R^3})$ time units. In UARA, every node in the network needs to know the position of the AUV that implies large overheads in disseminating knowledge of the location of the AUV to all nodes in the network. However, since the aggregation algorithm is deterministic, it will only involve an one-time dissemination of information to the nodes in the network.

C. UARA For Underwater Sparse Networks

After disseminating initial information to all the nodes, every node can utilize UARA to send data to the sink. Algorithm 2 describes UARA for underwater sparse networks when the AUV is within the transmission range of the sink. It is worth noting that for the nodes in S_3 and are not the current aggregation node, they should send their data to the neighbor node n' whose angle $\angle n'On^a$ is the least. Further, for nodes in S_k, $k \geq 4$, if their angle $\angle nOn^a \geq \theta$ (θ is a threshold, e.g., $\theta = \frac{\pi}{6}$), they should send data to their neighbor n' similarly. Otherwise, they could use GPSR to send data to n^a. If greedy forwarding fails in GPSR, the forwarding node n projects its neighbor nodes to Plane nOn^a and use perimeter forwarding to continue sending packets.

Input: n^v: the current location of the AUV
n^a: the current aggregation node
n^r: the current relay node

switch k: *the hops from the sink* **do**
  case *1*
    if $n! = n^v$ **then** Send packets to the sink;
    break;
  case *2*
    if $n == n^r \parallel has\_neighbor(n^v)$ **then**
      Send packets to the AUV;
    else
      if $has\_neighbor(n^r)$ **then**
        Send packets to the n^r;
      else
        Send packets to a neighbor node $n', n' \in S_3 \setminus A$;
      end
    end
    break;
  end
  case *3*
    if $n == n^a$ **then**
      Send packets to n^r;
    else
      Send packets to a neighbor node n' which satisfies that $\angle n'On^a$ is the least one in all the neighbors;
    end
    break;
  end
  otherwise
    if $\angle nOn^a \geq \theta$ **then**
      Send packets to a neighbor node n' which satisfies that $\angle n'On^a$ is the least one in all the neighbors;
    else
      Using GPSR to send data to n^a;
    end
  end
end

Algorithm 2: UARA for underwater sparse network ($n^v \in S_1$)

VI. SIMULATION RESULTS

In this section we show how UARA works in a finite underwater hemisphere network through simulation.

Our simulation is based on the simplified energy model described in Section III without considering the MAC or physical layer. We use a 3D grid sensor deployment on underwater hemisphere regions with different size and sparse network density.

A. Network Lifetime

Without loss of generality, we establish a 3D grid underwater hemisphere networks. Firstly, we set the gird length l equal to r, the underwater transmission range. Figure 3 shows the lifetimes of static underwater hemisphere networks and networks with one AUV by using different routing algorithms. R is the radius of the networks and all the lifetimes are normalized by setting the lifetime upper bound of $\frac{E}{R^3e}$ for static networks to 1. GF stands for the lifetime using greedy forwarding in static network without AUVs which are quite close to the upper bound of $\frac{E}{R^3e}$. SR shows the lifetime using

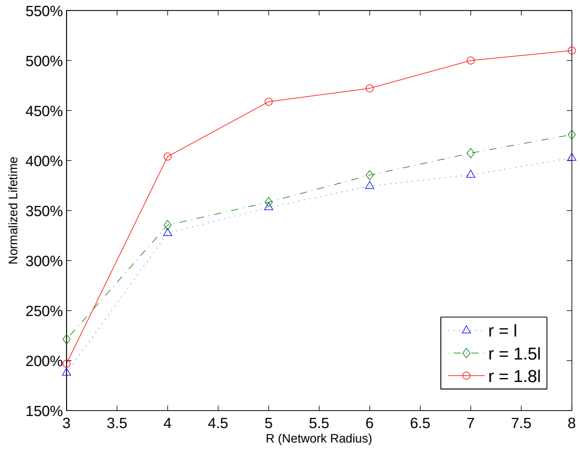


Fig. 4. The Network lifetime for 3D grid underwater hemisphere networks

static routing stated in Section IV . The results show that SR can improve the lifetime by 200%. LP presents the lifetime by using a dynamic routing stated in Section IV and calculated by linear programming. The dynamic routing is that all the packets generated from the nodes which are farther than the AUV to the sink should send to the AUV first and then the AUV will relay them to the sink; other packets need not relay by the AUV. Due to the complexity of the linear optimization problem, we only conduct the experiments on networks with $R \leq 6$. Nevertheless, the results still show that when the network radius R increases, the improvement of DR is closer to the upper bound of $\frac{8E}{eR^3}$.

B. Lifetime Improvement By Using UARA

Figure 4 depicts the lifetime improvement by using UARA. Although we assume dense and large networks in Section IV to derive the lifetime bounds, the improvement for sparse density and moderate size is considerable. We set the transmission range r equal to l, $1.5l$ and $1.8l$ whose corresponding density ρ are 1, 3.375 and 5.832 respectively. We test these sparse networks based on different network radius R from 3 to 8. For example, in the most sparse 3D grid network when $r = l$, UARA can improve the lifetime by 300% or above when $R \geq 4$; in a moderate dense network when $r = 1.8l$, UARA can improve the lifetime by 400% or above. Meanwhile, the results suggest that the improvement ratio is a nondecreasing function of the network size and density.

VII. Conclusion and Future Work

In this paper, the problem of network lifetime prolongation in 3D UWSNs has been investigated by considering the interactions between an underwater sensor network with an AUV. An underwater hemisphere network model has been proposed and we prove that in this model, the improvement of lifetime by using one AUV is upper bounded by a factor of eight and the AUV only needs to stay within two hops away from the sink. Also, we have presented UARA, a joint mobility and routing algorithm whose performance in terms of network lifetime comes close to the upper bound and AUVMS, a mobile scheme for the AUV to decrease its energy consumption.

We are currently considering how to use multiple AUVs to improve lifetime for UWSNs. We also plan to extend UARA to dynamic underwater networks in which locations of underwater sensors will be inflected by water flow movement.

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APPENDIX

A. Lifetime for nodes in S_3

Similarly, the nodes in set A will be left with enough energy for transmitting their own traffic after they have acted as aggregation nodes.

For nodes in $S_3\backslash A$, they need to relay the data generated by nodes in S_2 and S_3. There will be $\frac{22}{3}\pi\rho$ nodes in $S_3\backslash A$ and they must relay $\frac{52}{3}\pi\rho$ packets to the aggregation node in each time unit, $\frac{14}{3}\pi\rho$ from S_2 and $\frac{38}{3}\pi\rho$ from S_3. These packets should be relayed for at most $3\pi+1$ hops to reach the line OM. Then they need one more hop to send them to the aggregation node n^a. Therefore, a packet from S_2 or S_3 will be relayed for no more than $3\pi+2$ hops by nodes in $S_3\backslash A$. We denote a shell of $[i-1+r, i-1+r+\Delta r]$ as $Shell_{i,r}$ in the following discussion. There will be $2\pi(i-1+r)^2\rho\Delta r$ nodes in $S_3\backslash A$ and they will be symmetrically distributed around the shell. Therefore, since the symmetry, the traffic load in this shell can be evenly distributed. On the average each node in $S_3\backslash A$ will deliver packets for $\frac{26}{11}$ nodes in S_2 and S_3 including itself. In order to distribute the load evenly among different shells, we need to map $\frac{26}{11}\pi(3+2r-r^2)\rho\Delta r$ nodes in S_2 and S_3 to nodes in $Shell_{3,r}\backslash A$ and deliver the packets generated by them only through nodes in this shell. We can build such a mapping as follows: First, map S_2 and S_3 nodes to the $Shell_{3,r=1}\backslash A$, then decrease r and map inner shells in sequence, until we reach the innermost shell of $Shell_{3,r=0}$. When mapping nodes to a particular shell $Shell_{3,r}$, all nodes in $\{S_3\backslash A\} \cap \{[r+2+\Delta r, 3]\}$ would have already been mapped to $\frac{26}{11}$ nodes in S_2 and S_3. Therefore, when we are at $Shell_{3,r}$, total numbers of nodes in S_2 and S_3 which have already mapped will be $\frac{26}{11}\int_{x=r}^{1} 2\pi\rho(2x-x^2+3)\,\mathrm{d}x = \frac{52}{33}\pi\rho(r^3-3r^2+9r+11)$. The nodes in S_2 and S_3 which can communicate with a node in $Shell_{3,r}$ are in the area of $[r+1, 3]$, which has $\frac{2}{3}\pi\rho(26-r^3-3r^2-3r)$ nodes in total. Since $\frac{2}{3}\pi\rho(26-r^3-3r^2-3r)$ is always bigger than $\frac{52}{33}\pi\rho(r^3-3r^2+9r+11)$ for $0<r\leq 1$, this shows that there are unmapped nodes in S_2 and S_3 which can be mapped to $Shell_{3,r}$. Therefore, we can build a mapping from the $\frac{22}{3}\pi\rho$ nodes in $S_3\backslash A$ exactly being mapped to $\frac{22}{3}\pi\rho$ nodes in S_2 and S_3. Since each node in $Shell_{3,r}$ will have to relay $\frac{26}{11}$ nodes and each packet is routed for at most $(3\pi+2)$ hops. The lifetime for any node in $S_3\backslash A$ is at least $\frac{11E}{26(3\pi+2)e}$. When $R>6$, we can guarantee the lifetime of them will be lager than $\frac{8E}{R^3 e}$.

B. Lifetime for nodes in S_k with $k \geq 4$

The nodes in S_k with $k \geq 4$ will have to relay data generated in S_k and $\overline{H_k}$. First consider the packets generated in S_k. For nodes in $Shell_{k,r}$, the packets generated in this shell will be relayed to the line OM by nodes in the shell. These packets should travel at most π in angle before reaching to the line OM. Then it also need to be relayed one more hop to reach some node on line OM with exactly $k-3$ distance to the aggregation node. Therefore, the maximal hops a packet will travel in $Shell_{k,r}$ will be $\pi(k-1+r)+1$. Since there are $2\pi\rho(k-1+r)^2\Delta r$ nodes in $Shell_{k,r}$, the shell will generate $2\pi\rho(k-1+r)^2\Delta r$ packets in each time unit. During the network lifetime which is $\frac{8(E-E')}{R^3 e}$, the total energy consumption for this part will be upper bounded by:

$$\begin{aligned} E_1(k,r) &\leq 2\pi\rho(k-1+r)^2\Delta r \times \frac{8(E-E')}{R^3 e} \times e \\ &\quad \times \pi(k-1+r)+1 \\ &= \frac{16\pi\rho(k-1+r)^2(\pi(k-1+r)+1)}{R^3} \\ &\quad \times (E-E')\Delta r \end{aligned} \tag{11}$$

The next part is the packet generated by nodes in $\overline{H_k}$. The nodes in $Shell_{k,r}$ only will relay the traffic when the distance between the current aggregation node n^a and the sink is $2+r$. And there will be $2\pi\rho(2r^2+2r+1)\Delta r$ aggregation points whose distance to the sink is $2+r$. Each of them will be used at most $\frac{E-E'}{Ne}$ time units. Therefore, the nodes in $Shell_{k,r}$ will need to route traffic from $\overline{H_k}$ for at most $2\pi\rho(2r^2+2r+1)\frac{E-E'}{Ne}\Delta r$ time units. Since there will be at most N packets from $\bar{H}_k$ passing though $Shell_{k,r}$ per time unit, the total energy consumption during the lifetime will be upper bounded by:

$$\begin{aligned} E_2(k,r) &\leq 2\pi\rho(2r^2+2r+1)\Delta r \times \frac{E-E'}{Ne} \times N \times e \\ &= 2\pi\rho(2r^2+2r+1)(E-E')\Delta r \end{aligned} \tag{12}$$

Since there are $2\pi\rho(k-1+r)^2\Delta r$ nodes in $Shell_{k,r}$, the total energy which could be used for relaying will be $2\pi\rho(k-1+r)^2(E-E')\Delta r$. Therefore, the total residual energy for nodes in $Shell_{k,r}$ will be lower bounded by:

$$\begin{aligned} E_{re}(k,r) &\geq 2\pi\rho(k-1+r)^2(E-E')\Delta r \\ &\quad - [E_1(k,r)+E_2(k,r)] \\ &= 2\pi\rho(E-E')\Delta r[(-r^2+(2k-4)r+k^2-2k) \\ &\quad - \frac{8(k-1+r)^2(\pi(k-1+r)+1)}{R^3}] \\ &\geq 2\pi\rho(E-E')\Delta r[k^2-2k-\frac{8k^2(\pi k+1)}{R^3}] \\ &= \frac{2\pi\rho(E-E')\Delta r}{R}[Rk^2-(2R+8\pi)k-1] \end{aligned} \tag{13}$$

When R is bigger than $4\pi+\frac{1}{8}$, the total residual energy will be greater than 0. Since the traffic will be distributed evenly among nodes in $Shell_{k,r}$, the residual energy will be also be evenly distributed among them and no node in $\bigcup_{k\geq 4} S_k$ will die before $\frac{8E}{R^3 e} - \frac{64E}{R^6 e}$ when $R > 4\pi+\frac{1}{8}$.