

SURFACE-LEVEL GATEWAY DEPLOYMENT FOR UNDERWATER SENSOR NETWORKS

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ABSTRACT

The performance of underwater sensor networks (UWSNs) is greatly limited by the low bandwidth and high propagation delay of acoustic communications. Deploying multiple surface-level radio-capable gateways can enhance UWSN performance from many aspects. In this paper, we mainly focus on the surface gateway deployment, which is modelled as an optimization problem. Integer Linear Programming (ILP) is used for solving variations of the deployment optimization problem. The tradeoff between the number of surface gateways and the expected delay and energy consumption is analyzed. We conduct simulations to evaluate the benefits of surface gateway optimization and investigate the effect of acoustic channel capacity and the underwater sensor node deployment pattern. Our results show the significant advantages of surface gateway optimization. The results also provide useful guidelines for real network deployment.

I. INTRODUCTION

In recent years underwater sensor networks (UWSNs) have emerged as an enabling technology for underwater monitoring and exploration applications, including scientific, commercial and military applications [1], [2], [3], [4], [5], [6]. Compared to their remote-sensing counterparts, UWSNs can provide localized and more precise data acquisition. However, UWSN is facing many unique challenges. Unlike terrestrial wireless sensor networks, underwater sensor networks cannot use electromagnetic waves due to the quick absorption in water. Acoustic waves are usually considered a practical solution for UWSNs. The dependency of UWSNs on underwater acoustic communications is particularly challenging. The most limiting factor of underwater acoustic communications is the extremely low propagation speed of sound, which is roughly 1500 m/s, subject to slight changes due to pressure, temperature and salinity variations [7]. This is five orders of magnitude slower than the 3×10^8

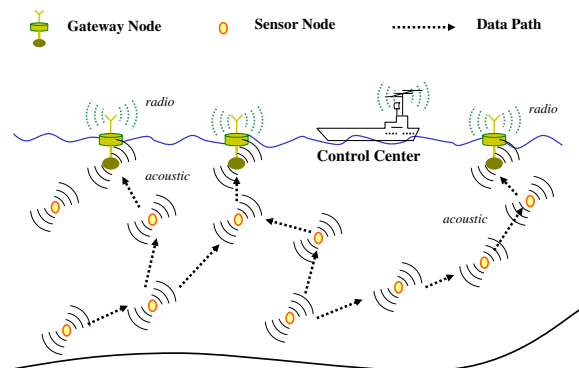


Fig. 1. An illustration of UWSN with multiple surface gateways

m/s propagation speed of electromagnetic waves. Such high propagation delay can cause high end-to-end delay, which could be greatly limiting for interactive applications, and other monitoring applications where response time is critical.

One way to mitigate the high propagation delay in acoustic communications is to deploy multiple surface-level gateways. Fig. 1 illustrates an underwater sensor network with multiple surface gateways. In the sensor network, each sensor node can monitor and detect environmental events locally and then transfer these measurements, through the network, to a surface gateway node (also referred to as a sink for the UWSN), which then relay data to the control station. Different from single sink networks, in a multiple-sink underwater sensor network, as illustrated in Fig. 1, instead of having to use long underwater paths to reach the unique surface sink, underwater sensor nodes can send data packets towards their nearest surface gateways. A surface gateway, then uses electromagnetic waves to forward packets to the control station. Considering that electromagnetic wave propagation is orders of magnitude faster than acoustic wave propagation, it is safe to assume that surface gateways can send packets to the control station in negligible time and with relatively small energy consumption

(acoustic communications consume much more energy than radio communications [5]). In this way, all the surface gateways (or sinks) form a *virtual sink*.

Although architectures employing multiple surface gateway nodes were mentioned in [5], [8], there is no formal study on surface gateway deployment: neither analysis on the effect of using multiple surface gateways on the network energy consumption or delay characteristics has been conducted, nor guidelines on deployment of such a multi-sink architecture have been provided. In this paper, we study the problem of surface gateway deployment and present guidelines for deciding the number and locations of surface gateway nodes given an underwater sensor network deployment scenario. We focus on optimizing the cost of surface gateway deployment, by finding the minimum number and the locations of surface gateway nodes required to achieve a given design objective, which can be communication delay, energy consumption, fault-tolerance, or a combination of them. The surface gateway deployment problem is formulated as an optimization problem, modelling the routing of data packets from underwater sensor nodes to the virtual sink, under link capacity and flow conservation constraints. A variety of objective functions are presented. To provide insight into the relationship between the different design parameters, we also conduct simulation experiments. Results show the significant advantages of surface gateway optimization.

The rest of this paper is organized as follows. In Section II, the network model and assumptions regarding the surface gateway deployment problem are presented and justified. In Section III, the surface gateway deployment problem is formulated as an optimization problem. In Section IV, the sample problems chosen to analyze the effect of various constraints on the deployment are described and the results are presented. In Section V, several closely related studies are briefly discussed. Finally, in Section VI, conclusions are drawn and some future work is presented.

II. PROBLEM SETTING

Generally speaking, there are two approaches to handle the surface gateway deployment problem, 1) solving the underwater deployment and the surface-level deployment problems jointly, or 2) solving each of them separately. It is understood that solving both underwater and surface deployment problems jointly will lead to optimal solutions that are better, or at least as good as, the outcome of the two-phase approach. However, since the objective of the research presented here is to analyze the effect of surface gateways deployment on the overall underwater sensor network performance, *we prefer to*

fix the underwater deployment and therefore opt for the latter option. Thus, we assume that there is a pre-existing underwater deployment that has been reached by a way or another.

1) *Network Model:* The surface gateway deployment problem can be modelled a 3-D graph optimization problem. The nodes of the graph represent underwater sensors and candidate surface gateway positions. The problem is to choose a subset of the candidate surface gateway positions to satisfy a set of flow conservation constraints, interference constraints, deployment cost constraints (e.g., the number of surface gateways), and/or the network performance requirements. The selection of the candidate positions is sophisticated enough to be considered as a separate problem on its own, and we defer it to future research. In this work, the candidate surface gateway positions are given and they need to satisfy the connectivity constraints, i.e. each underwater node should have a path to at least one candidate surface position. Further, each underwater sensor node is associated with a packet generation rate, and all generated packets are expected to deliver to one or more surface gateways, i.e., reaching the virtual sink.

2) *Assumptions:* Here we detail some assumptions we make in this work. First, we assume all acoustic transceivers are homogeneous, thus, the communication range is constant for all nodes. Further, we assume that underwater sensor nodes are either stationary or their motion is correlated strongly enough to assume that their relative locations are fixed. In addition, the communication links are symmetric. If we do not consider queueing delays (e.g., caused at MAC or routing layer), it is reasonable to assume that packets travelling in the reverse direction will follow the reverse paths.

To reduce the problem complexity, we assume a simplified interference model, in which a node can transmit only when it is not receiving anything from its neighbors. In fact, this is consistent with the the half-duplex status of current acoustic modems. The assumption of ignoring queueing delays can be well justified when the network is very lightly loaded. In such case, the probability of packet collision is too small to affect the performance.

III. PROBLEM FORMULATION

The surface gateway deployment problem can be formulated as a graph optimization problem. In this section, we detail the definitions, the constraints and possible objective functions.

A. Definitions

The network is modelled as a graph, in which nodes represent the underwater sensor nodes and candidate

surface gateway positions, and edges represent pair-wise communication links.

1) *Nodes*: Let V be the set of all underwater sensor nodes, T be the set of candidate surface node positions, and V' be the set of all nodes, i.e. $V' = V \cup T$.

Let $I(v)$ be the set of nodes within the communication range of node v , i.e. $I(v) = \{w : w \in V', v \neq w, d(v, w) \leq R\}$, where $d(v, w)$ denotes the distance between v and w , and R is the communication range of sensor nodes.

2) *Edges*: Let E be the set of all edges $e = (v, w)$, such that $v \in V, w \in I(v)$. Let $E_{out}(v)$ and $E_{in}(v)$ demote the outgoing and incoming edge set of v respectively. Then $E_{out}(v) = \{e(v, u) : (v, u) \in E\}$, $\forall v \in V$, and $E_{in}(v) = \{e(u, v) : (u, v) \in E\}$, $\forall v \in V'$. Note that for any surface gateway node, the outgoing edge set is Φ , since the surface gateways only receive data (no relaying function).

3) *Data Generation and Flow*: Let $g(v_i)$ be the packet generation rate at node $v_i \in V$, and let G be the total data generation rate, i.e., $G = \sum_{v \in V} g(v)$. Further, we use $f(e)$ to denote the total data flow (in both directions) on edge e .

4) *Gateway Presence Indicator*: Let $x(t_i)$ be a binary variable that defines the surface gateway deployment at location t_i :

$$x(t_i) = \begin{cases} 1 & \text{if a node deployed at } t_i \\ 0 & \text{otherwise} \end{cases}, \quad \forall t_i \in T. \quad (1)$$

B. Constraints

We describe the various constraints as follows.

1) *Deployment Constraints*: Data can only be received at locations where surface nodes are deployed:

$$f(e_i) \leq x(t_j)G, \quad \forall t_j \in T, e_i \in E_{in}(t_j). \quad (2)$$

In other words, no data will be received at locations without gateways.

2) *Interference Constraints*: The simple interference model adopted in this work assumes that a node cannot send while it is receiving, which implies that the total data transfer rate sent and received at any node can not exceed the maximum capacity B of its communication link. Thus, for underwater sensor nodes we have

$$\sum_{e_o \in E_{out}(v)} f(e_o) + \sum_{e_i \in E_{in}(v)} f(e_i) < B, \quad \forall v \in V, \quad (3)$$

and for surface candidate gateways we have

$$\sum_{e_i \in E_{in}(t)} f(e_i) < B, \quad \forall t \in T. \quad (4)$$

3) *Per-Node Flow Conservation*: Flow conservation implies that for underwater sensor nodes, the sum of the flows leaving a node equals the sum of the flows entering that node plus the local data generation rate, that is

$$\sum_{e_o \in E_{out}(v)} f(e_o) - \sum_{e_i \in E_{in}(v)} f(e_i) = g(v), \quad \forall v \in V. \quad (5)$$

4) *End-to-End Flow Conservation*: Each surface node can act as a sink, and all surface gateways together form a virtual sink. Thus, a packet generated by any source, must eventually be received by a surface node. End-to-end flow conservation here means that the total data generation rate must equal the total data absorption rate by all surface node sensors, that is

$$\sum_{t_j \in T} \sum_{e_i \in E_{in}(t_j)} f(e_i) = G. \quad (6)$$

5) *Deployment Cost*: For the multi-sink architecture, the deployment cost of surface gateways is of critical concern. To optimize the network performance, such as minimizing delay or energy consumption, using a limited number of surface nodes, N , we should include the following constraint:

$$\sum_{t_i \in T} x(t_i) \leq N. \quad (7)$$

C. Objective Functions

With an objective function, by solving the set of equations (1) through (7), an optimal deployment is obtained in the form of an assignment to the set of binary variables $x(t_i)$. In the following, we present some representative objective functions we have explored, namely minimizing the expected delay, minimizing the expected energy consumption, and minimizing the maximum delay.

1) *Minimizing Expected Delay*: The objective is to minimize the expected end-to-end delay for all packets. The end-to-end delay for a packet is the sum of the per-hop delay over the entire path from the source that generates the packet to the sink that receives it. Since queuing delays (caused at MAC or routing layer) are not considered in this work, the per-hop delay consists of transmission delay and propagation delay. The delay t on an edge e can be written as

$$t(e) = t_s(e) + t_p(e) = \frac{L}{B} + \frac{l(e)}{v_p},$$

where L is the packet length in bits, B is the channel capacity in bits per second, $l(e)$ is the distance between the nodes at the two ends of e , and v_p is the propagation speed of sound in water. The expected delay for all packets then can then be written as

$$E[t(e)] = \frac{1}{G} \left(\sum_{e \in E} f(e)t(e) \right),$$

and the corresponding objective function will be

$$\text{Minimize}(E[t(e)]).$$

2) *Minimizing Expected Energy Consumption:* The objective is to minimize the expected end-to-end energy consumption, i.e., the energy consumed in the network for a packet to travel from its source to a sink. The energy consumed ε to transmit a packet over edge e can be written as

$$\varepsilon(e) = \pi_s(e)t_s = \pi_s(e)\frac{L}{B},$$

where $\pi_s(e)$ is the transmission power used on edge e for one unit of data.

Similar to the expected delay, the expected energy consumption can be written as

$$E[\varepsilon(e)] = \frac{1}{G} \left(\sum_{e \in E} f(e)\varepsilon(e) \right),$$

and the corresponding objective function will be

$$\text{Minimize}(E[\varepsilon]).$$

3) *Minimizing Maximum Delay:* The objective functions presented so far reflect the expected performance of the overall network. A more precise optimization of performance can consider data packets generated by individual sources separately. For example, the objective can be to minimize the worst-case expected delay seen by data packets originating at any specific source node. To do that, we define $f_{v_s}(e)$ as the portion of $f(e)$ originating at source node v_s . It follows that $f(e) = \sum_{v_s \in V} f_{v_s}(e), \forall e \in E$. In this case, flow conservation constraints have to be detailed such that every sub-flow has its own conservation equation as follows.

$$\begin{aligned} \sum_{e_o \in E_{out}(v_i)} f_{v_s}(e_o) - \sum_{e_i \in E_{in}(v_i)} f_{v_s}(e_i) \\ = \begin{cases} g(v_s) & \text{if } v_i = v_s, \\ 0 & \text{otherwise} \end{cases}, \forall v_s, v_i \in V, \end{aligned} \quad (8)$$

and

$$\sum_{t_j \in T} \sum_{e_i \in E_{in}(t_j)} f_{v_s}(e_i) = g(v_s), \forall v_s \in V. \quad (9)$$

The objective function can then be written as

$$\text{Minimize} \left[\text{Max}_{v_s \in V} \left(\sum_{e \in E} f_{v_s}(e)t(e) \right) \right].$$

IV. SIMULATION STUDY

In this section, we use simulations to study the effect of different parameters on the results of the deployment optimization problem.

A. Simulation Settings

Throughout the experiments, we fix the packet length $L = 400\text{bits}$, the propagation speed of sound in water $v_p = 1500\text{m/s}$, and the transmission power $\pi_s = 1\text{watt}$ (we ignore receiving and idle power, which are much less than transmission power). We also fix the area of network deployment to a square of $600\text{m} \times 600\text{m}$ horizontal extent, and fix the candidate gateway deployment positions to a 5×5 mesh of points spaced 150m apart. The communication range for both underwater sensors nodes and acoustic interface of the surface gateways nodes is $R = 150\text{m}$. The depth of all underwater sensors is set to 100m such that each of the underwater sensors, regardless of its horizontal location, is within the communication range of at least one surface gateway candidate position. This guarantees that the optimization problem can be made feasible by choosing a large enough number of surface gateway nodes, N . Finally, the data generation rate at each underwater sensor is set to a constant, $g(v) = 1\text{packet/second}$, $\forall v \in V$. We use the following two underwater deployment patterns in our experiments.

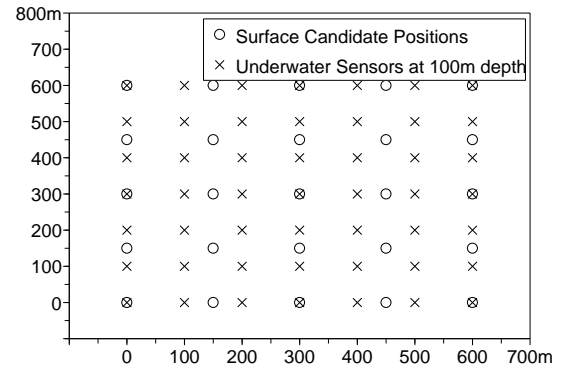


Fig. 2. Sample uniform underwater deployment problem

1) *Uniform Underwater Deployment:* The uniform underwater deployment was chosen because the uniformity of the solution simplifies the process of verifying the results. The chosen underwater deployment consists of a 7×7 planar mesh of sensor nodes. The distance between two adjacent nodes is 100m , and therefore the nodes cover the entire $600\text{m} \times 600\text{m}$ area. This problem setting is illustrated in Fig. 2.

2) *Random Underwater Deployment:* This deployment is similar to the uniform underwater deployment, except that the 49 underwater sensor nodes are distributed at random within the $600\text{m} \times 600\text{m}$ underwater area. The problem setting is illustrated in Fig. 3.

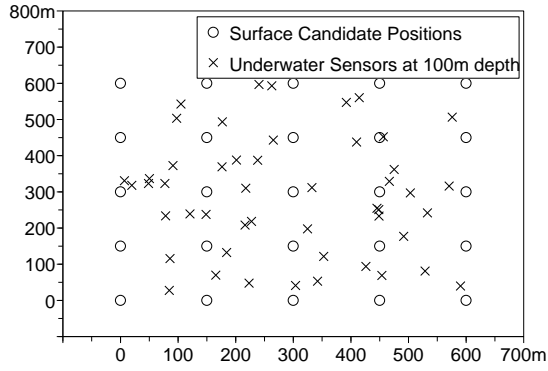


Fig. 3. Sample random underwater deployment problem

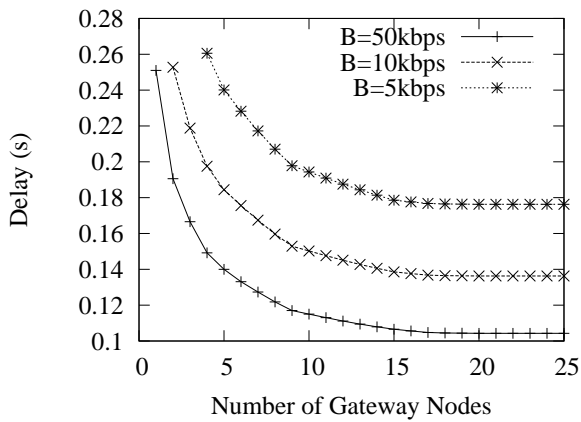


Fig. 4. Average delay, uniform underwater deployment

B. Results and Analysis

In this section, we show the results of the deployment optimization problem with a couple of critical parameters. We demonstrate the benefits of the multi-sink architecture (using average delay and average energy consumption as sample network performance metrics). We also provide some useful guidelines (e.g., how channel capacity and underwater deployment affect the network performance) for real network deployment.

1) *Benefits of Multi-Sink Architecture:* When the number of allowed surface-level gateway nodes increases, the performance characteristics, such as average delay or average power consumption, is expected to improve. To verify this, we vary the number of allowed surface nodes from 1 to 25 nodes and solve the optimization problem. Results show that an increase in the number of surface gateways can dramatically enhance the network performance, especially when the network is lightly loaded. For example, Fig. 4 shows that the expected delay corresponding to $B = 50\text{kbps}$ can be reduced from 0.26s to 0.16s by using four

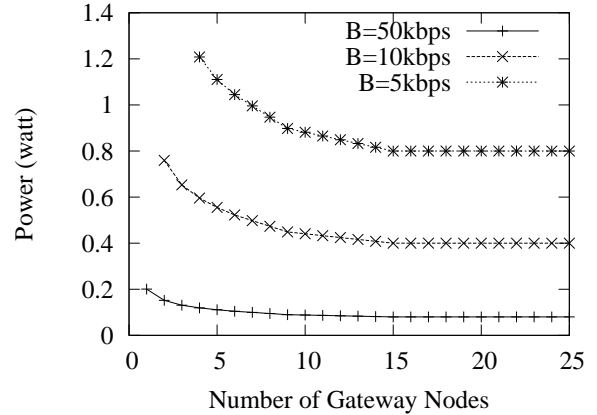


Fig. 5. Average energy, uniform underwater deployment

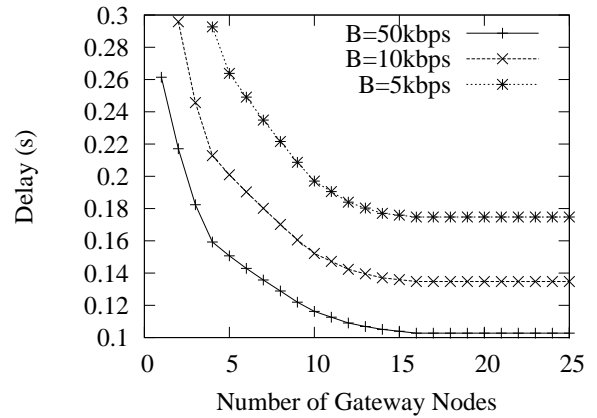


Fig. 6. Average delay, random underwater deployment

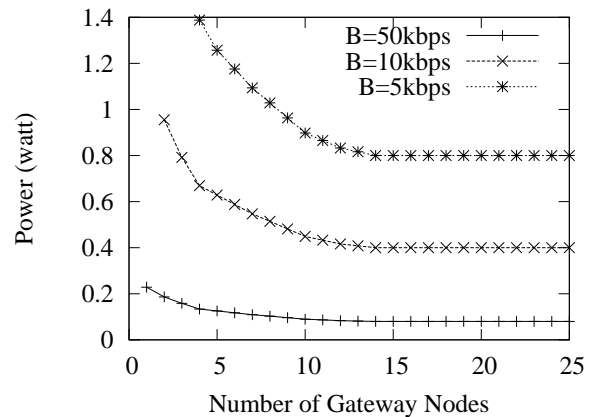


Fig. 7. Average energy, random underwater deployment

surface gateways instead of one, as exactly shows the benefits of the multi-sink architecture. It is also worth noting that the improvement gained by adding a surface gateway diminishes as the number of surface gateways increases. After a certain number (a threshold) of surface gateways, depending on the underwater deployment (as well as other factors), additional surface nodes have no positive effect on the performance of the network. This is due to the fact that when the threshold is reached, every underwater sensor node could communicate with a surface gateway at the nearest candidate position. Therefore, any further addition of surface nodes becomes redundant.

2) *Effect of Channel Capacity:* Intuitively, when the ratio of the total data generation rate to the per-node channel bandwidth increases, the minimum number of surface-level nodes required to make the problem feasible increases. This is due to the fact that surface gateways will saturate with incoming traffic and therefore more nodes will be needed to handle the additional traffic corresponding to the increased data generation rate. On the other hand, increasing channel capacity reduces the network load, and consequently our assumptions about ignoring queuing delays becomes more realistic.

To demonstrate the effect of channel capacity on the quality of the solution, we solve the deployment optimization problem for different link capacities, namely 5kbps , 10kbps and 50kbps . Simulation results show that the performance improvement resulting from the addition of more surface gateway nodes diminishes when the network load increases, confirming our expectations as explained before. For example, Fig. 5 shows that the heavily-loaded network, corresponding to the channel capacity of 5kbps has a smaller dynamic range of $0.2/0.08 = 2.5$ than the lightly-loaded network corresponding to $B = 50\text{kbps}$, whose dynamic range is equal to $1.2/0.8 = 1.5$. Fig. 4 and Fig. 5 show the effect of varying the channel capacity, in the case of uniform underwater deployment, on the expected delay and energy consumption, respectively. Fig. 6 and Fig. 7 show the effect of varying the channel capacity, in the case of random underwater deployment, on the expected delay and energy consumption, respectively.

3) *Effect of Underwater Deployment Pattern:* When the set of candidate surface-gateway positions is pre-set, the locations of underwater sensors and the distribution of data generation load among them are expected to affect the benefit of adding more surface gateways. If underwater sensors are clustered in groups, less surface-gateways are expected to feasibly route all traffic to the surface, compared to the case when underwater sensors are spread evenly over the deployment area. On the

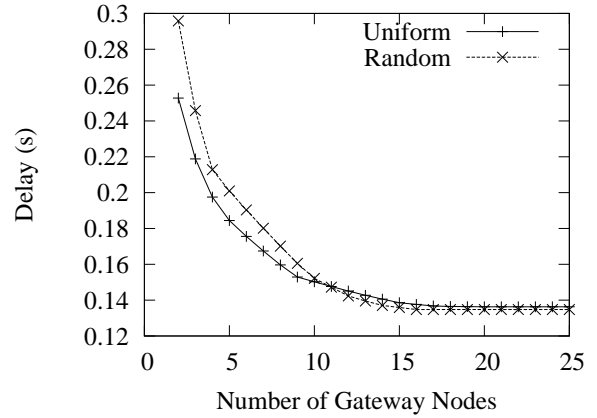


Fig. 8. Average delay, uniform vs. random underwater deployment

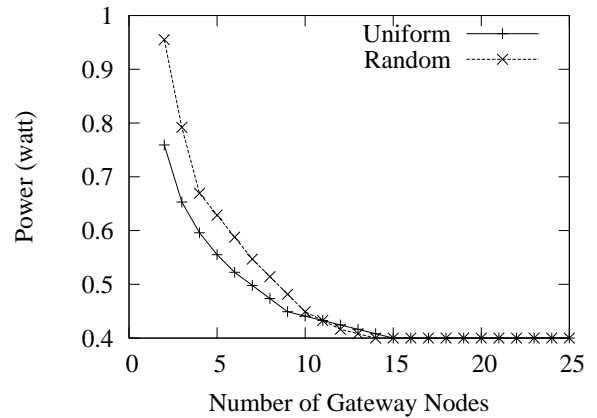


Fig. 9. Average energy, uniform vs. random underwater deployment

other hand, clustering increases the odds of collision, and in the case of high traffic loads, can negatively affect delay and energy consumption. To study the effect of underwater sensor deployment on the result of the surface gateway deployment optimization, we use two underwater deployment patterns, namely, a 2-D mesh uniform deployment and a planar random deployment.

Fig. 8 and Fig. 9 compare the results of the uniform underwater deployment case and the random underwater deployment case, at a fixed channel capacity of 10kbps . When the number of surface gateways is small, the randomly-distributed underwater deployment suffers more congestion and therefore performs slightly poorer than the uniformly-distributed counterpart, both in delay and energy consumption metrics. When the number of surface gateways increases, the effect of congestion diminishes and the effect of clustering grows stronger. After a certain number of surface gateways, the energy consumption of the randomly-distributed underwater deployments converges to that of the uniformly-distributed case, because eventually each underwater node becomes one hop away from a surface gateway. Although Fig. 8

shows that the delay of the randomly-distributed case eventually becomes lower than the uniformly-distributed case, this is not necessarily always true. The problem instance shown in Fig. 3 happens to have an average distance between underwater nodes and candidate surface positions lower than that in the uniformly-distributed case in Fig. 2. Therefore the randomly-distributed case exhibits less average propagation delay as in Fig. 8.

We have also run the experiments for several random underwater deployments. The results exhibit the same trends though the exact values of delay and energy are slightly different. We use this set of experiments to mainly show the underwater deployment does have effect on the network performance. Thus, to get better solutions, it is necessary to consider the underwater and surface deployments jointly, which we would like to investigate in our future work.

V. RELATED WORK

In this section, we briefly discuss several related research studies on underwater sensor network deployment and multi-sink architecture.

Triangular-grid deployment pattern for 2-D UWSN was proposed in [9]. The objectives is to minimize the number of sensors needed to achieve the sensing and communication coverage of a target area. An interesting attempt to formulate the 3-D UWSN point-coverage deployment problem as an ILP was presented in [10]. The solution of the ILP decides relay node deployment, routing and link-scheduling. Throughout the work, it is assumed that a single sink for the entire UWSN deployment, and the overall power consumption is used as an optimization objective. Neither of these two studies consider the multiple-sink network architecture.

The only research study in the frame of multiple sinks we found is [8], in which Seah and Tan investigated the use of multi-sink architecture to enhance the underwater sensor network reliability. In this study, the same message is directed to more than one of the multiple sinks, with the assumption that if any of the sinks gets the message then it is considered delivered successfully. The simulation results showed that high reliability benefits can be achieved at the cost of reasonable increase in energy consumption. The surface gateway (i.e., sink) deployment problem was not considered in this work.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, the surface gateway deployment problem has been formulated as an optimization problem, the solution of which gives the minimum number and the optimal locations of surface gateway nodes, with a variety of optimization goals. Simulation results confirm

the potential for performance improvement using multiple surface gateways: reducing both average delay and energy consumption. It has been shown that the effect of the added surface gateways depends on the channel capacity (or the network loading level), as well as the given underwater sensor deployment pattern.

The work presented here helps to pave the way for a wide variety of future research. One possible improvement is to optimize underwater and surface deployments jointly. Another improvement is to include a more elaborate interference model and take MAC protocol effect into the formulation, to get more accurate results. Another related future research direction is to analyze the effect of the choice of surface candidate locations on the quality of the solution, and use the results to devise methods to calculate the candidate positions that best suit a given underwater deployment.

REFERENCES

- [1] G. G. Xie and J. Gibson, "A Networking Protocol for Underwater Acoustic Networks," in *Technical Report TR-CS-00-02*, Department of Computer Science, Naval Postgraduate School, December 2000.
- [2] J. Proakis, E.M.Sozer, J. A. Rice, and M.Stojanovic, "Shallow Water Acoustic Networks," *IEEE Communications Magazines*, pp. 114–119, November 2001.
- [3] I. F. Akyildiz, D. Pompili, and T. Melodia, "Challenges for Efficient Communication in Underwater Acoustic Sensor Networks," *ACM SIGBED Review*, vol. Vol. 1, no. 1, July 2004.
- [4] J. Heidemann, W. Ye, J. Wills, A. Syed, and Y. Li., "Research Challenges and Applications for Underwater Sensor Networking," in *IEEE Wireless Communications and Networking Conference*, Las Vegas, Nevada, USA, April 2006.
- [5] J.-H. Cui, J. Kong, M. Gerla, and S. Zhou, "Challenges: Building Scalable Mobile Underwater Wireless Sensor Networks for Aquatic Applications," *Special Issue of IEEE Network on Wireless Sensor Networking*, May 2006.
- [6] J. Partan, J. Kurose, and B. N. Levine, "A Survey of Practical Issues in Underwater Networks," in *Proc. of ACM International Workshop on UnderWater Networks (WUWNet)*, September 2006, pp. 17–24. [Online]. Available: <http://prisms.cs.umass.edu/brian/pubs/partan.wuwnet2006.pdf>
- [7] L. Berkhovskikh and Y. Lysanov, *Fundamentals of Ocean Acoustics*. New York, Springer, 1982.
- [8] W. K. Seah and H.-X. Tan, "Multipath Virtual Sink Architecture for Underwater Sensor Networks," in *OCEANS 2006 Asia Pacific Conference*, Singapore, may 2006.
- [9] D. Pompili, T. Melodia, and I. F. Akyildiz, "Deployment Analysis in Underwater Acoustic Wireless Sensor Networks," in *The First ACM International Workshop on UnderWater Networks (WUWNet'06)*, September 2006.
- [10] L. Badia, M. Mastrogiovanni, C. Petrioli, S. Stefanakos, and M. Zorzi, "An Optimization Framework for Joint Sensor Deployment, Link Scheduling and Routing in Underwater Sensor Networks," in *WUWNet'06*, September 2006, pp. 55–63.