# Efficient Surface Gateway Deployment
# For Underwater Sensor Networks

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***Abstract*—Deploying multiple surface-level radio-capable gateways enhances the performance of underwater acoustic sensor network. The locations of gateways have to be carefully selected to maximize the benefit in a cost-effective way. In this paper, we show how to efficiently solve the surface gateway deployment optimization problem, using heuristic approaches. The results of applying these proposed algorithms to a variety of practical deployment scenarios suggest that these heuristics are nearly optimal for practical cases.**

***Index Terms*—Underwater sensor networks; multi-sinks; surface gateways; deployment optimization.**

## I. INTRODUCTION

In the last decade, underwater sensor networks (UWSNs) have emerged as an enabling technology for underwater monitoring and exploration applications, including scientific, commercial and military applications [3], [4], [5], [6], [7]. 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 absorbtion 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 [8]. This is five orders of magnitude slower than the $3 \times 10^8$ 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.

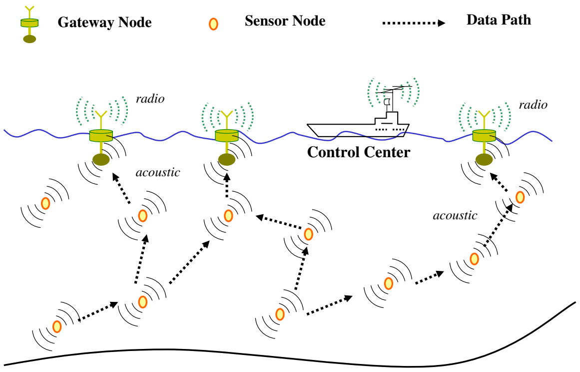

Fig. 1. An illustration of UWSN with multiple surface gateways

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 (which is also referred to as a sink for the UWSN), which then relays data to the control station. Instead of having to use long underwater paths to reach a single surface sink, a multiple-sink underwater sensor differs from single sink networks in that nodes can send data packets towards their nearest surface gateways, as illustrated in Fig. 1. 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 since acoustic communications consume much more energy than radio communications [7]. In this way, all the surface gateways (or sinks) form a *virtual sink*.

In our previous work [1], we studied in detail the factors and benefits of such an architecture and forumulated the gateway optimal deployment as an integer linear programming (ILP) problem.

In this paper, we study the performance of heuristic solutions to the gateway optimal deployment problem and show that high-performance solutions can be efficiently found in polynomial time, enabling the off-line solution of large-scale deployment problems and opening the door to investigating the dynamic re-deployment of gateway nodes.

The rest of this paper is organized as follows. In Section II, we briefly present the findings of related research on the deployment of underwater sensor network and multi-sink architecture. In Section III, the network model and assumptions regarding the surface gateway deployment problem are presented and justified. In Section IV, the surface gateway deployment problem is formulated as an optimization problem. In Section V, the proposed heuristic algorithms for solving the deployment optimization problem are layed out and analyzed. In Section VI, we present the results of solving vairous sample problems. Finally in Section VII, we draw our conclusions for this part of our research.

## II. RELATED WORK

In this section, we briefly present the findings of related research on the deployment of underwater sensor network and multi-sink architecture. In [10], Pompili et al. investigated the use of triangular-grid pattern for 2-D UWSN deployments. The objectives was to minimize the number of sensors needed to achieve the sensing and communication coverage of a target area. In [11], Badia et al. formulated the deployment of underwater relay nodes in a 3-D UWSN as an ILP, assuming that MAC will be achieved static link scheduling. In [9], Seah and Tan investigated the use of multi-sink architecture to enhance the reliability of underwater sensor networks. The surface gateway deployment optmization, however, is not addressed in their work.

## III. PROBLEM SETTING

We use the same problem setting described in [1], which 1) assumes that there is a pre-existing underwater deployment and 2) seeks to find the optimal deployment locations for a given number of surface gateways.

*1) Network Model:* The surface gateway deployment problem is modelled a graph optimization problem. The nodes of the graph represent underwater sensors and candidate surface gateway positions, and the problem is to choose a subset of the candidate surface gateway satisfying a set of flow conservation constraints, interference constraints and either constraints on the number of surface gateways or the required network performance. The selection of the candidate positions is sophisticated enough to be considered a separate problem on its own, and therefore it is deferred to future research. For the purpose of this work, the set of candidate surface points is considered a given and has to satisfy connectivity constraints as a pre-condition, i.e. each underwater node has to have a path to at least one candidate surface position, taking into account the communication ranges of the involved nodes.Associated with each underwater sensor node is a packet generation rate. Surface gateway nodes have to collect all generated data packets. Further assumptions are detailed in the next section.

*2) Assumptions:* All acoustic transceivers are assumed to be homogeneous and therefore the communication range is assumed to be constant for all nodes. We assume that sensor nodes are either stationary or that their motion is correlated strongly enough to assume that their relative locations are fixed. The scenario being considered is that of a monitoring network, where most of the traffic originates at sensor nodes and travels through the network to the common sink station. Therefore, the analysis is limited to the, possibly multi-path, route from each underwater sensor to the virtual sink. Under the assumption of homogeneity and ignoring queuing delays, it can also be assumed that packets traveling in the reverse direction will follow the reverse paths, and therefore its magnitude can be added to the traffic generated by the respective sensor nodes. To reduce the problem complexity, we assume a simplified interference model, i.e. a node can transmit only when it is not receiving anything from its neighbors. Queuing delays, such as those caused by the MAC protocol, are ignored. This assumption can be realistic if the network is very lightly loaded, and the probability of collision is too small to affect the performance. The effect of limited channel capacity was investigated in [1].

## IV. PROBLEM FORMULATION

The surface gateway deployment problem is formulated as an optimization problem. The formulation consists of a basic set of constraints that can be augmented with a variety of objective functions. This section details the basic definitions, the constraints and possible objective functions.

### A. Definitions

The network is modelled as a graph, in which nodes represent the underwater sensors and surface gateways, 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 the two nodes, and $R$ is the communication range for any sensor node.

*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 $E_{out}(v) = \{e(v, u) : (v, u) \in E\}, \quad \forall v \in V$, and $E_{in}(v) = \{e(u, v) : (u, v) \in E\}, \quad \forall v \in V'$

*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., $G = \sum_{v \in V} g(v)$. Let $f(e)$ be the total flow in edge $e$.

*4) Gateway Presence Indicator:* Let $x(t_i)$ be a set of binary variables that defines the surface gateway deployment as follows:

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

### B. Constraints

Constraints can be classified into the following sets.

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

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

*2) Interference Constraints:* The simple interference model adopted in this paper 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't exceed the maximum capacity $B$ of the communication link. This implies for underwater sensor nodes that

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

And for surface candidate gateways

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

*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

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

*4) End-to-End Flow Conservation:* Surface nodes work as gateways, and therefore a packet generated by any source, must eventually be received by a surface node. Flow conservation implies that the total data generation rate must equal the total data absorption rate by all surface node sensors

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

*5) Number of Surface Gateways:* If the objective of the optimization is to minimize delay or energy consumption using a limited number of surface nodes, $N$, the following constraint can be used.

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

### C. Objective Functions

The problem can be solved for a choice of optimization goals. We arbitrarily choose the average delay as an optimization goal to illustrate the performance of the heuristic algorithms proposed here. 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 or delays caused by the medium access control protocol are not considered in this work, the per-hop delay consists of transmission delay and propagation delay. The delay $t$ or 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 velocity of sound waves in water.

The expected delay can then be written as

$$E[t(e)] = \frac{1}{G}\Big(\sum_{e \in E} f(e).t(e)\Big)$$

And the corresponding objective function will be

$$\text{Minimize}\big(E[t(e)]\big) \quad (8)$$

## V. GREEDY HEURISTIC APPROACHES

Heuristic approaches for solving similar optimization problems, such as the warehouse location problem, have already been investigated before in reseach [2]. Their findings directed our attention to the greedy and greedy-interchange algorithms which proved to be effective for solving large scale warehouse location problems [2]. In the rest of this section both the greedy and greedy-interchange algorithms for solving the deployment optimization problems are presented along with a complexity analysis of both algorithms.

### A. Greedy Algorithm

In the greedy approach, the near-optimal deployment of $m$ gateways is developed by adding (to an already existing near-optimal deployment of $m-1$ gateways) a gateway at the location that minimizes the objective function.

Let the original ILP problem instance be $\mathcal{P}$, and initially let $\mathcal{P}\prime = \mathcal{P}$. For $j = 1, 2, \cdots, m$ do:

1) Modify the "Number of Gateways" constraint in $\mathcal{P}\prime$ such that the RHS of equation (7) is $j$
2) Solve $\mathcal{P}\prime$, and let $x\prime(.)$ be the solution (if one can be found)
3) For each $t_i \in T$ such that $x\prime(t_i) = 1$ add a constraint $x(t_i) = 1$ to $\mathcal{P}\prime$ and loop.

The algorithm quits unsuccessfully whenever $\mathcal{P}\prime$ at step (2) is infeasible. This means that the greedy algorithm will need modification in order to handle the special case when one single surface gateway is unable to serve the entire underwater sensor network. If the reason of infeasibility is bandwidth limitations, the data generation rates at all underwater nodes, $g(v_i)$ are divided by $m/j$, to obtain a feasible solution. If again the problem in infeasible, then the underwater network has to be partitioned and each partition has to be solved spearately, and then the greedy algorithm takes over from $j =$ the number of partitions + 1.

### B. Greedy-Interchange Algorithm

The interchange algorithm takes a solution and tries to improve it iteratively. At each iteration, the algorithm searches for a pair of candidate deployment locations, one active and one inactive, whose interchange is most beneficial, i.e., whose interchange leads to the maximum decrease of the objective function.

Our implementation of the greedy-interchange is slightly different than the greedy-then-interchange standard approach. Instead we start from a greedy partial solution, and allow at most one of the already selected candidate locations to be exchanged for a better unselected location at the same time a new location is added to the solution in a greedy manner. We achieve this by replacing step (3) of the greedy algorithm above with the following step: Augment $\mathcal{P}\prime$ with the constraint:

$$\sum_{x_i \in X, x_i\prime = 1} x_i \geq j - 1$$

### C. Complexity Analysis

The Integer Linear Programming formulation of the deployment problem is an NP-hard problem. To find the optimal solution we have to evaluate $\binom{n}{m}$ possible deployment, and in each deployment we have to solve the optimal routing problem. Solving the optimal routing problem for a fixed underwater deployment can be assumed to take approximately constant time for any gateway deployment being evaluated. Therefore, the runtime of the optimal gateway deployment algorithm is $O(\binom{n}{m}k)$, where $n$ is the number of candidate gateway locations, $m$ is the number of gateways to be deployed, $O(k)$ is the runtime upper bound for solving the optimal routing problem for the given underwater and gateway deployment.

The greedy approach, however, has to evaluate $\binom{n}{1} + \binom{n-1}{1} \cdots \binom{n-m+1}{1}$ deployments, which means that the runtime of the algorithm will be $O(nmk)$.

The greedy-interchange, as a compromise solution between the optimization and the greedy approach, has to evaluate $\binom{n}{2} + \binom{n-1}{2} + \binom{n-2}{2} + ... + \binom{n-m+2}{2}$, which means that the runtime of the algorithm will be $O(n^2mk)$.

## VI. SIMULATION STUDY

To study the quality of the solutions generated using the greedy approach and the greedy-interchange approach, we solve several problems using four methods, namely exhaustive search, randomized, greedy and greedy interchange and then report the percentage of quality loss (increased delay) for each approach. We also record the runtime for solving each problem using each algorithm and compare the results with

To estimate the quality of a randomized approach we randomly generate 100 solutions for each problem and then calculate the average value of the objective function as well as its standard deviation. Throughout our experiments the 0.001-confidence interval was found to be $\leq \pm 6\%$ of the value of the mean.

### A. Simulation Settings

Throughout the experiments, we fixed the packet length $L$=400 bits, the propagation velocity $v_p$=1500 m/s, and the transmission power is to a constant $\pi_s$=1 watt. We also fixed the area of deployment to a square area of 600mx600m horizontal extent, and fixed the candidate gateway deployment positions to a 5x5 mesh of points spaced 150m apart. The communication range for both underwater sensors nodes and acoustic interface of the surface gateways nodes is fixed at $R$=150. 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 problems can be made feasible by choosing a large enough limit on the number of surface gateway nodes, $N$. Finally the data generation rate at each underwater sensor is set to a constant, $g(v) = 0.01$ packet per second, $\forall v \in V$. The following two underwater deployment patterns were used:

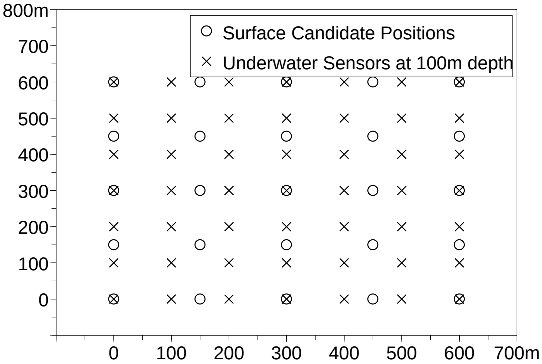

Fig. 2. Sample uniform underwater deployment problem

*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 7x7 planar mesh of sensor nodes. The distance between two adjacent nodes is 100m, and therefore the nodes cover the entire 600x600m area.

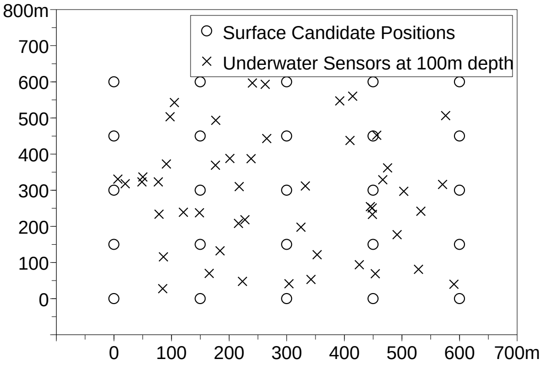

Fig. 3. Sample random underwater deployment problem

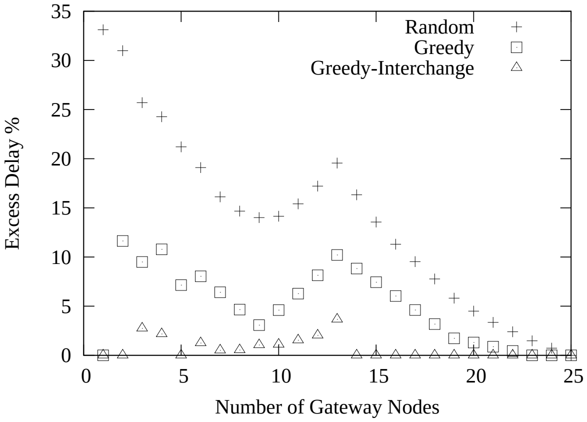

Fig. 4. Quality of solutions, uniform underwater deployment

*2) Random Underwater Deployment:* Similar to the Uniform Underwater Deployment, except that the 49 underwater sensor nodes are distributed at random within the 600x600m underwater area.

### B. Results and Analysis

Simulations were conducted in order to evaluate the performance of each of the four solutions. The results for the uniform underwater deployment are shown in Figure 4, and the results for the random underwater deployments are shown in Figure 5, 6 and 7 .

In both cases, the greedy approaches produces results very close to the optimal solution, with the greedy-interchange doing superiorly good.

## VII. CONCLUSIONS

In this paper, we have shown that the greedy approach can produce near optimal solutions to the gateway deployment problem in underwater sensor networsk. We

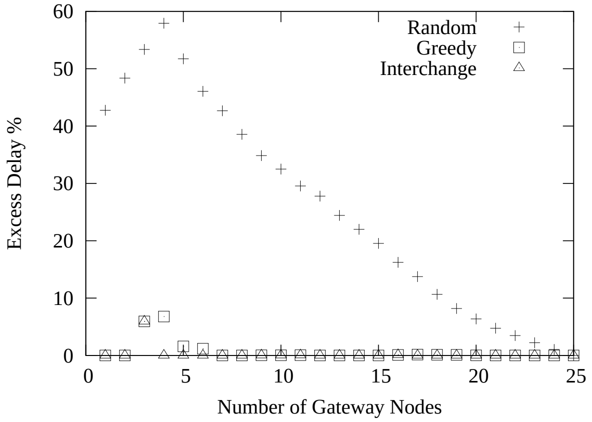

Fig. 5. Quality of greedy solutions, sample random underwater deployment 1

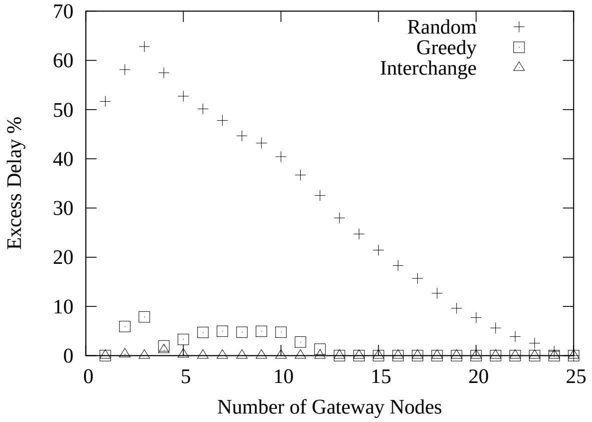

Fig. 6. Quality of greedy solutions, sample random underwater deployment 2

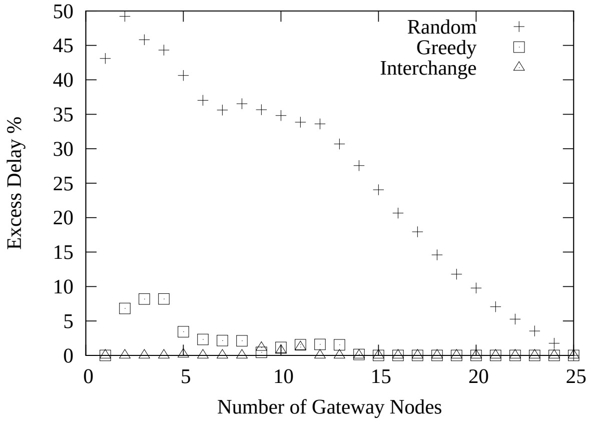

Fig. 7. Quality of greedy solutions, sample random underwater deployment 3

have also shown that the quality of the solution can be further improved by employing the greedy-interchange technique at the cost of increasing algorithm complexity from $O(n^2)$ to $O(n^3)$.

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