Multi-stage AUV-aided Localization for Underwater Wireless Sensor Networks

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***Abstract*—Underwater Wireless Sensor Networks (UWSNs) are expected to support a variety of civilian and military applications. Sensed data can only be interpreted meaningfully when referenced to the *location* of the sensor, making localization an important problem. In terrestrial WSNs, this can be achieved through a series of message exchanges (via RF communications) between each sensor and Global Positioning System (GPS) receivers. However, this is infeasible in UWSNs as GPS signals do not propagate through water.**

Acoustic communications is currently the most viable mode of wireless communications underwater. However, underwater acoustic channels are characterized by harsh physical layer conditions with low bandwidth, high propagation delay and high bit error rate. Moreover, the variable speed of sound, due to variations in temperature, pressure and salinity, and the non-negligible node mobility due to water currents pose a unique set of challenges for localization in UWSNs.

In this paper, we present a multi-stage AUV-aided localization scheme for UWSNs. The proposed method combines the flexibility and localization accuracy of an AUV-aided localization, the energy efficiency of "silent localization" and improved localization coverage with k-stage localization based on sensor nodes. We evaluate the performance of the proposed scheme in terms of the localization coverage, accuracy and communication costs using simulations. We show that while improved performance with multiple stages is traded off with higher communication costs in general, the latter can be minimized while maintaining good performance with an appropriate choice of the acoustic communication range.

I. INTRODUCTION

Over the last few years, we have observed a growing interest in Underwater Wireless Sensor Networks (UWSNs). One important reason is that they can improve ocean exploration and fulfil the needs of a multitude of underwater applications, including: oceanographic data collection, warning systems for natural disasters (e.g., seismic and tsunami monitoring), ecological applications (e.g., pollution, water quality and biological monitoring), military underwater surveillance, assisted navigation, industrial applications (offshore exploration), etc. For example, in offshore engineering applications, the sensors can measure parameters such as foundation strength and mooring tensions to monitor the structural health of deepwater mooring systems.

Two common communications architecture for UWSNs are shown in Figure 1. In addition to underwater sensor nodes, the network may also comprise surface stations and autonomous underwater vehicles (AUVs). Regardless of the type of deployment (outdoor, indoor, underground or underwater), the location of the sensors needs to be determined for meaningful interpretation of the sensed data. Since RF communications does not work well underwater, the use of the well-known Global Positioning System (GPS) is restricted to surface nodes. Hence, message exchanges between submerged UWSN nodes and surface nodes needed for localization must be carried out using acoustic communications. Unfortunately, underwater acoustic channels are characterized by long propagation delays, limited bandwidth, motion-induced Doppler shift, phase and amplitude fluctuations, multipath interference, etc [1]. These unique characteristics pose severe challenges towards designing localization schemes that fulfil the following desirable qualities:

- **Accurate**
  The location of the sensor for which sensed data is derived should be accurate and unambiguous for meaningful interpretation of data.
- **Fast**
  Since nodes may drift due to water currents, the localization procedure should be fast so that it reports the actual location when data is sensed.
- **Wide Coverage**
  The localization scheme should ensure that all nodes in the network can be localized.
- **Low Communication Costs**
  Since the nodes are battery-powered and may be deployed for long durations, it should not waste energy for unnecessary transmissions during the localization procedure.

In [2], we presented a survey of recent localization schemes proposed specifically for UWSNs by (i) describing their salient features; (ii) categorizing them into infrastructure-based vs infrastructure-less schemes, and single-stage vs multi-stage schemes; (iii) providing a qualitative evaluation in terms of speed, accuracy, coverage and communication costs; and (iv) identifying important challenges that should be, but have yet been, addressed.

Infrastructure-less localization schemes do not rely on costly infrastructure (e.g., GPS receivers on the sea surface or fixed references on the seabed) and can be deployed in an ad-hoc manner (e.g., using AUVs as mobile references). Hence, these

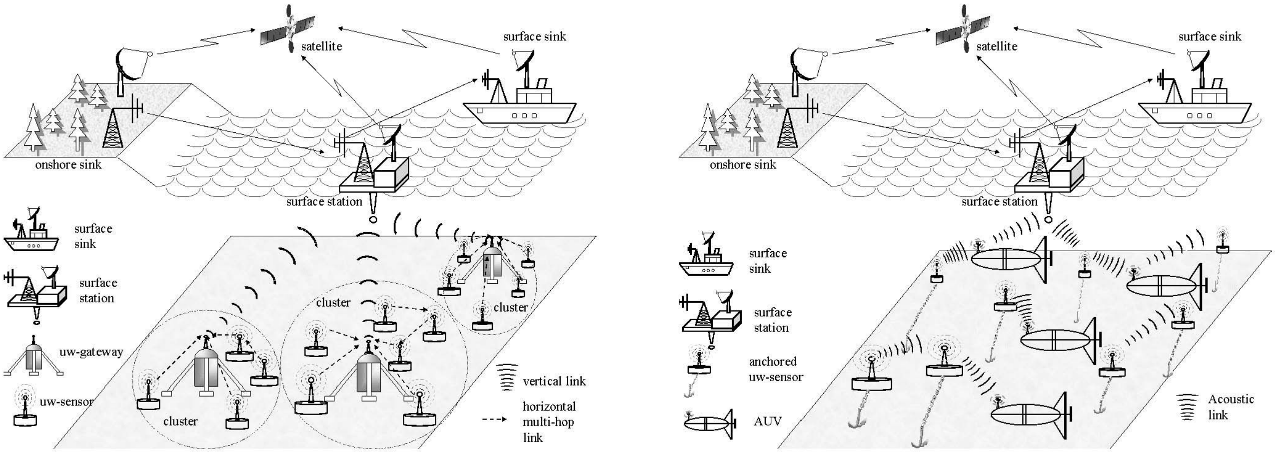


Fig. 1. A 2-D (left) and 3-D (right) communications architecture for UWSNs [1].

schemes are promising for emergency and tactical surveillance applications. While the use of AUVs is promising, its large scale use is restricted by its prohibitively high cost; this imposes a limitation on the achievable localization coverage, particularly in areas around rocks and reefs.

In this paper, we propose a multi-stage, AUV-aided underwater localization scheme, where nodes localized by the AUV in the first stage become reference nodes for localizing the remaining (non-localized) nodes in the UWSN in subsequent stage(s). We demonstrate the efficacy of our proposed scheme in terms of its coverage, localization accuracy and communication costs using extensive simulations.

This paper is organized as follows: In Section II, we give a brief overview of AUV-aided and multi-stage underwater localization schemes. In Section III, we present some definitions and describe our scheme. We evaluate our scheme based on the simulation results in Section IV. Finally, we present some concluding remarks and outline possible future research directions in Section V.

II. RELATED WORK

Recently, a multitude of range-based localization schemes have been proposed specifically for UWSNs that rely on the presence of *reference* nodes with known position coordinates. Such reference nodes could be *fixed* (e.g., deployed on surface buoys or on the seabed) or *mobile* (e.g., AUVs). Each *ordinary* node estimates its distance from each reference node by exchanging beacons with the reference nodes (or single reference node at various locations) and measuring the time (or time difference) of arrival. It then runs some localization algorithm (e.g., using multi-lateration or bounding box method) using the distance estimates, where d+1 independent measurements are needed to localize a d-dimensional space.

In the "**AUV-Aided**" localization technique proposed in [3], the sensor nodes can be dropped into the ocean and will move with the water currents while an AUV will traverse the UWSN periodically. The AUV obtains position updates by rising to the surface to use GPS, and then dives to a predefined depth and starts exchanging three types of messages with the ordinary nodes: *wakeup*, *request* and *response*. "wakeup" messages are sent by the AUV as it enters the network to declare its presence. Ordinary nodes that receive this message will respond with a "request" message to commence range measurement. "request/response" messages are exchanged between the AUV and ordinary nodes to estimate their positions according to the round trip time. This scheme does not assume any fixed infrastructure or time synchronization. In certain cases, simulation results show that 100% localization can be achieved with only 3% position error. However, the localization time required (up to 2 hours) and the message exchange phase to localize the nodes can be improved.

The "AUV-Using Directional Beacons" scheme (**UDB**) [4] is similar to [3] except for the following differences: (i) it proposes more accurate and efficient ways for localization based on simple calculations using *directional* instead of omnidirectional beaconing; and (ii) it reduces energy consumption by integrating "Silent Localization" [5] for the localization process. However, it takes more time to localize all the nodes using directional beacons because the AUV needs to traverse the network at least twice, and the impact of node mobility on its accuracy could be significant.

Instead of AUVs, the "Dive'N'Rise" (**DNR**) localization scheme [6] uses mobile beacons whose diving/rising is controlled by a weight/bladder mechanism. These beacons update their positions at the surface, and broadcast them when they dive to a certain depth. This is a low-cost scheme that can localize 100% of the nodes with relative small positioning error and can reduce communication costs and energy using "Silent Localization". However, the scheme uses 25 DNR beacons for 1km × 1km × 1km underwater column, which is extremely expensive because it requires 25 GPS and 25 moving devices. Moreover, under actual operating conditions, the DNR beacons will be strongly affected by the surface currents, which will degrade the localization accuracy.

In [7], the authors present a multi-stage enhancement to DNR – termed "**Multi-stage DNR**". When an ordinary node receives at least three messages from the mobile reference at non-collinear locations, it computes its own location. After that, it becomes a reference node and helps to localize the remaining ordinary nodes, provided it lies below the maximum dive depth of DNR mobile beacons.

III. MULTI-STAGE AUV-AIDED UNDERWATER LOCALIZATION

In this section, we describe our proposed Multi-stage AUV-aided localization technique for UWSNs, aimed at improving the "**Multi-stage DNR**" scheme by replacing the DNR with an AUV. This expands the coverage of the mobile beacon in the first stage while utilizing the multi-stage concept to localize the remaining (un-localized) nodes.

We consider an UWSN that comprises an AUV and ordinary nodes that dive to a known depth (provided by pressure sensors) and remain static (by fixing with anchors) during the localization process. Moreover, all nodes can communicate (omni-directionally) with the AUV and other nodes by sending or receiving acoustic signals. The AUV can surface to obtain its coordinates using GPS signals, and can be pre-programmed to dive to a given depth (provided by pressure sensors) and traverse a given path. As with the ordinary nodes, the AUV is equipped with an omni-directional antenna and communicate with nodes via acoustic signals. We assume that the AUV as well as the ordinary nodes are all time synchronized.

A. Procedure for AUV

We begin by describing the procedure for the AUV, as illustrated in Fig. 2. Initially, the AUV floats on the surface and can obtain its coordinates from GPS. After that, it will dive to a pre-programmed depth with the help of a pressure sensor and start traversing the sensor network following a pre-programmed path. However, its actual path will deviate due to underwater currents. To correct for / minimize its positional errors, the AUV can (i) surface periodically to obtain GPS updates; or (ii) be equipped with high precision navigation tools (e.g., Doppler Velocity Log) that limits this deviation to an acceptable level. In this study, we assume that the AUV (i) follows a sinusoidal path in the X-Y plane; (ii) is subject to underwater currents in the Y direction; and (iii) is equipped with navigation tools to limit its positional error to 5m.

The three-stage message exchange (*wakeup*, *request* and *response*) between ordinary nodes and the AUV proposed in the "**AUV-Aided**" localization technique [3] incurs high energy consumption, which is undesirable as it is difficult to replenish the power source in UWSNs once they are deployed. We propose to reduce this energy consumption by applying some concepts of "Silent Positioning" as proposed in [5], where ordinary nodes remain silent and do not need to transmit at all during the first stage.

We define the beacon structure to comprise three components: *time stamp*, *coordinates* and *identifier*. The time stamp indicates the time the beacon is created at the AUV and is used by the ordinary node to estimate its distance from the AUV using the Time of Arrival approach (ToA). The second component comprises the coordinates of the AUV at the instant of beaconing, which together with the distance estimates, are used to estimate the ordinary node's coordinates. Finally, the identifier, ID, indicates if the beacon originated from the AUV (ID = 1) or from a localized ordinary node (ID = 0).

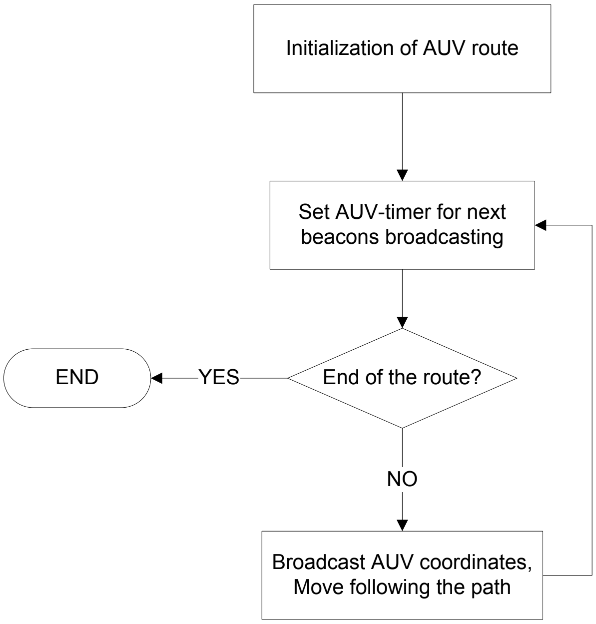


Fig. 2. Procedure for AUV in Multi-stage, AUV-aided Localization.

B. Procedure for Ordinary Nodes

Initially, each ordinary node sets a beacon counter, m to 0, initializes a timer, t, set its status to "unlocalized" ($Node\_stat$ = UNLOC) and set the variable *IDsum* to 0. Each ordinary node at position (x,y) listens to the beacons broadcasted by the AUV. When it receives a message transmitted at t_1 when the AUV is at location (x_1, y_1), it updates m and estimates its distance, d_1, from the AUV using the average speed of sound underwater and the difference in the arrival time and time stamp. It then stores ($\tilde{x}_1$,$\tilde{y}_1$), which are the AUV's estimated coordinates, the identifier as well as the estimated distance d_1. This is repeated when it receives the next message transmitted at t_2 and so on, as illustrated in Figure 3 until it receives three beacons from non-collinear locations. The node can then solve for (x,y) using triangulation.

As stated before, z and z_i are known via pressure sensors. Using (x,y,z) and the stored coordinates ($\tilde{x}_i$, $\tilde{y}_i$, z_i), we can recompute the distance between the AUV and the node, $\tilde{d}_i$, i=1,2,3 as follows:

$$\tilde{d}_i^2 = (x - \tilde{x}_i)^2 + (y - \tilde{y}_i)^2 + (z - z_i)^2.$$

Then, the condition for the node to be localized and become a reference node is given as follows:

$$\max_{i=1:3} |d_i - \tilde{d}_i| \le \epsilon. \tag{1}$$

When a node becomes localized ($Node\_stat$ = LOC), it updates the variable *IDsum* by summing up the ID of the received beacons used to estimate its location to determine if it was AUV-localized (*IDsum* = 3 in this case). After a certain time-out (for the AUV to complete its beacon broadcast), all reference nodes will broadcast their (estimated) coordinates once from which (some of) the remaining ordinary nodes can localize themselves using the same technique as before (k=1). In this case, only the AUV-localized nodes will broadcast once. This procedure can be repeated (k >1) until no more ordinary node becomes localized to improve the coverage, albeit at the expense of higher communication costs, as shown in Figure 4. Figure 5 illustrates the interaction between the AUV and the ordinary nodes.

IV. SIMULATION RESULTS

We validate our proposed localization scheme using the Qualnet simulator [8]. We deploy between 100 to 200 ordinary nodes (in increments of 10) randomly in a 1000m × 1000m × 100m water volume, and we assume that they remain in a fixed position throughout the simulation duration. The AUV traverses the UWSN at a constant depth and constant speed (5m/s), following its sinusoidal path within a relative small error (up to 5m) in the Y direction due to underwater current. The communication range for the AUV and nodes varies between 150m, 225m and 300m. We use CSMA as the medium access control protocol and model the acoustic channel according to [9].

We evaluate and compare the performance of our proposed algorithm for $k = 1$ and $k > 1$ according to three criterion: i) *coverage*, described as the ratio of the localized nodes to the total number of nodes; ii) *localization error*, described as the average Euclidean distance between the estimated and real location of each node; and iii) *communication costs*, described as the total number of messages sent by the nodes, excluding the messages sent by the AUV. The energy consumption to localize a UWSN is directly linked with the total number of beacons sent by the nodes. We observe that the whole localization process lasts slightly less than 10 minutes.

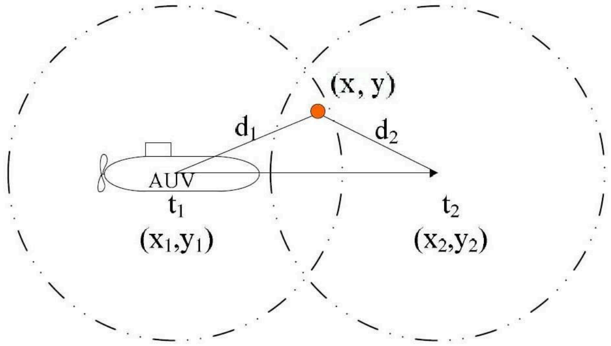


Fig. 3. Illustration of AUV-aided localization (Dotted line indicates acoustic communications range).

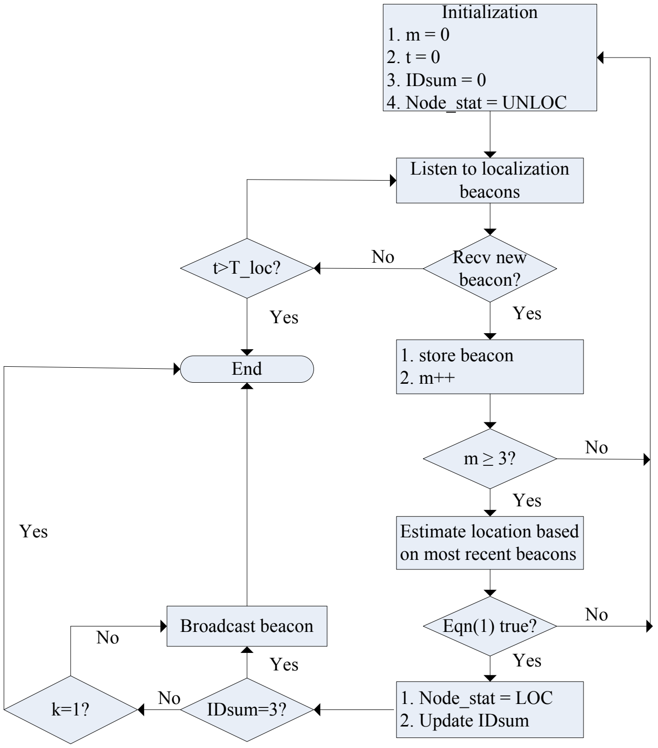


Fig. 4. Procedure for ordinary node in Multi-stage, AUV-aided Localization.

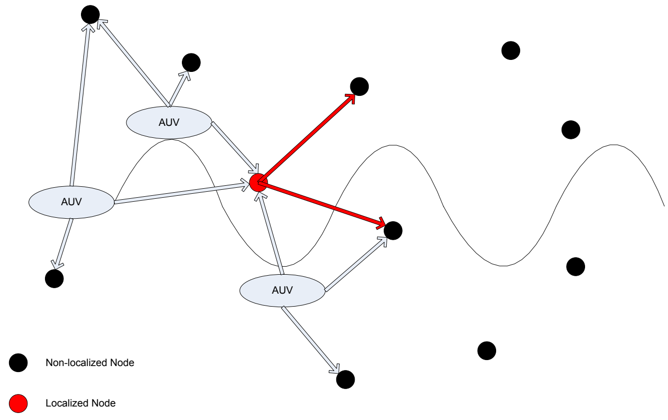
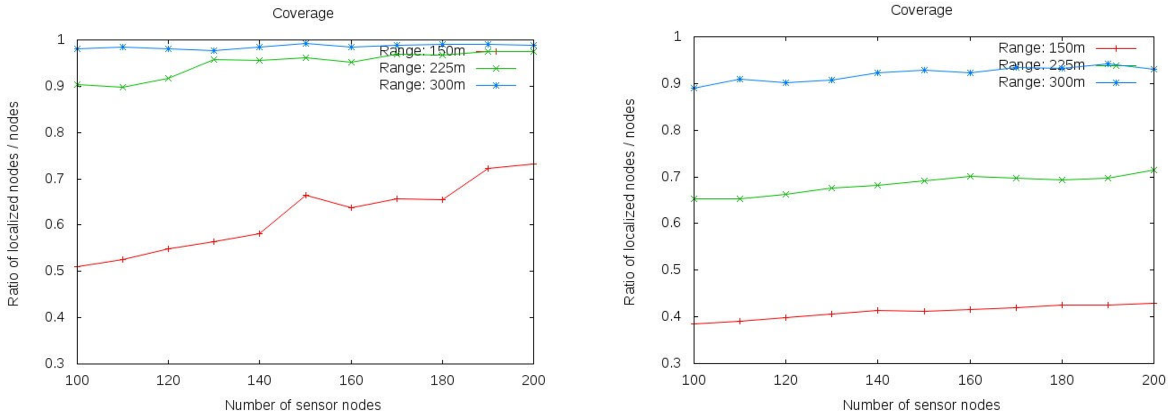


Fig. 5. Interaction between the AUV and sensor nodes.

A. Coverage

In Figure 6, we compare the coverage achieved for k = 1 and k > 1. As expected, the coverage for k > 1 is clearly higher than k = 1, with a gain of up to 30%. However, the achievable coverage is still quite low (up to 70%) with a short communication range (150m).

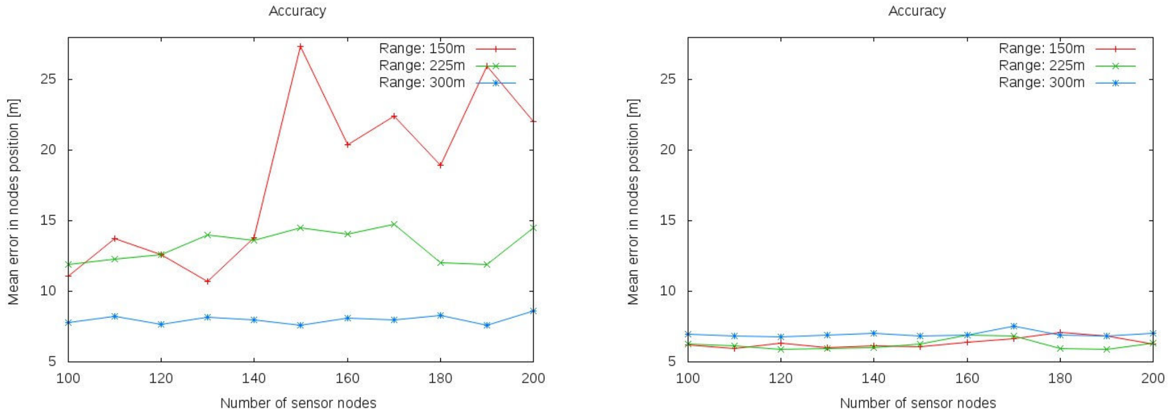
At a higher communication range of 300m, the coverage



(a)

(b)

Fig. 6. Coverage achieved with (a) $k > 1$ and (b) $k = 1$



(a)

(b)

Fig. 7. Localization accuracy achieved with (a) $k > 1$ and (b) $k = 1$

remains over 90% regardless of the network size, and the difference in performance between $k = 1$ and $k > 1$ becomes marginal. This is due to the fact that the AUV and the first set of reference nodes can localize almost the entire UWSN with acoustic range of 300m and thus, extending the multi-stage to $k > 1$ does not increase the performance as significantly as with smaller communication ranges.

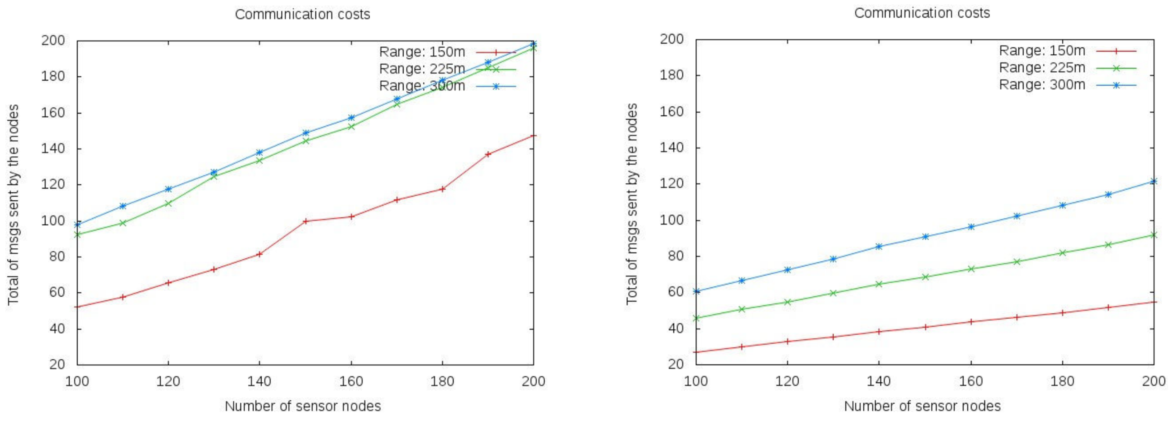
B. Localization Accuracy

We show the mean localization error in the estimated positions of the localized nodes for $k = 1$ and $k > 1$ in Figure 7. For $k = 1$, we can observe that, regardless of the communication range, the mean error in the nodes' position is approximately 6-7 meters. This is expected because all the localized nodes get their coordinates from the AUV (with a maximum position deviation of 5m) or from nodes that were localized using the AUV positions (which contributes cumulatively to the position error).

For $k > 1$, the mean localization error increases considerably especially for the lower acoustic range of 150m and 225m. This is due to the fact that the AUV and the first stage of reference nodes do not provide sufficient coverage to localize all nodes. Hence, the remaining ordinary nodes will use coordinates from other reference nodes and once their position is estimated, they will help to localize other nodes by broadcasting their coordinates, which will propagate the location error. The results show that by increasing the acoustic range to 300m, the localization error is similar for $k = 1$ and $k > 1$. This is because the AUV and the first stage of reference nodes can localize almost the entire UWSN, minimizing error propagation through the network.

C. Communication Costs

The third measure of our simulations is the communication costs, whose results are represented in Figure 8. These results are directly related to the coverage performances because of the fact that a node will not broadcast any beacon as long as it has not been localized. The communication costs increase linearly as we increase the total number of nodes in our UWSN. This linearity is explained by the fact that each sensor node is limited to broadcast only one beacon once localized and because the coverage ratio stays stable while increasing the total number of nodes. Finally, if the augmentation of the costs between $k = 1$ and $k > 1$ for 150m and 225m ranges results in higher coverage, in the case of a 300m range, the wastage of energy with $k > 1$ is less justifiable as the gain in



(a) (b)

Fig. 8. Communication costs with with (a) k = N and (b) k = 1

coverage is less insignificant.

V. Conclusion and Future Work

In this paper, we proposed a multi-stage AUV-aided localization technique for underwater wireless sensor networks (UWSN)s. The proposed method combines the flexibility and localization accuracy of an AUV-aided localization, the energy efficiency of "Silent Localization" and improved localization coverage with k-stage localization based on sensor nodes. We evaluated our proposed method for $k = 1$ and $k > 1$ with three different values of acoustic transmission ranges: 150m, 225m and 300m according to three criterions: coverage, accuracy and communication costs for a network comprising 100 to 200 fixed nodes deployed randomly in an underwater column measuring 1000m × 1000m × 100m. With $k > 1$, the localization process by the (non-AUV localize) reference nodes continue until no new ordinary node can be localized.

The whole localization process can be completed in less than 10 minutes with approximately 7 meters error in the positioning and can cover more than 95% of the whole network. In addition, we observe that with the lower acoustic ranges, the increase in coverage with $k > 1$ is achieved at the expense of higher localization error and communication costs compared to $k = 1$. However, with a 300m acoustic communications range, additional stages do not achieve a significant gain in terms of coverage and accuracy while incurring higher communication costs. Basically, this indicates that by employing an acoustic antenna with a reasonably long range (300m), a single-level of multi-stage is sufficient to achieve the best coverage and localization accuracy while preventing wastage of energy by broadcasting beacons unnecessarily.

For future work, we plan to (i) extend our scheme for three-dimensional localization; (ii) consider more realistic mobility current effects such as the meandering current mobility model [10]; and (iii) compare various AUV paths in evaluating our proposed scheme. In the long term, we hope to implement and evaluate the proposed scheme in an actual underwater environment.

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