# Underwater Wireless Sensor Networks: Efficient Localization Schemes using SemiDefinite Programming

Bo Dong and Ahmed M. Mahdy
Department of Computing Sciences
Texas A&M University-Corpus Christi
Corpus Christi, TX USA
bdong@tamucc.edu and ahmed.mahdy@tamucc.edu

*Abstract*— **Location awareness and distance estimation cannot be underestimated in wireless sensor networks especially for the marine environment. State-of-the-art localization research and approaches have been thoroughly reviewed to illustrate the challenges imposed by inaccurate distance measurements and noisy backgrounds. Compared to existing localization approaches, the SemiDefinite Programming approach delivers accurate distance measurements even in hostile backgrounds. In this paper, two localization schemes, namely Fixed-Position, and Magnified-Range, are proposed. The main idea behind the Fixed-Position scheme is to improve connectivity of the whole system. Magnified-Range is mainly based on the fact that anchors are special nodes that suffer less from energy constraints. Therefore, it is possible to magnify their radio range without impacting the energy consumption of the network. Magnified-Range differentiates between the radio range of anchors and regular sensor nodes. Performance evaluation and simulation results have shown that the proposed schemes offer robust localization. In fact, the Magnified-Range scheme improves localization accuracy by 20%. Future research will focus on three main challenges, namely 3-D simulations, hybrid localization systems, and real-life demonstrations.**

***Keywords-marine wireless sensor networks; underwater communication; localization; GPS; SemiDefinite Programming.***

## I. INTRODUCTION

The majority of the earth's surface is covered with water. As more research is conducted on underwater systems, data collection and environment monitoring become major components. This raises the need for an effective way to collect data and monitor the environment. Underwater wireless sensor networking offers an unmatched option. The characteristics of the underwater environment present researchers with many challenges, especially developing effective sensor communication and localization techniques. In terrestrial wireless sensor networks, the nodes use Radio Frequency (RF) to establish the communication infrastructure. In underwater environments, due to water absorption, RF does not deliver the same performance.

Compared to radio waves, sound has superior propagation characteristics in water, making it the preferred technology for underwater communications. However, since GPS may not work in underwater environments, acoustic signals bring many challenges to underwater sensor applications that require effective localization. Hence, there is a need to develop novel localization schemes that work well in the marine environment.

For the past few years, localization has become an indispensable factor of wireless sensor networks especially in tracking systems and environment monitoring. For many WSN applications, such as habitat monitoring, it is necessary to describe where the critical events occur. To obtain the location of sensor nodes, one can equip lightweight GPS receivers on all sensors but this significantly increases network cost and may defeat the whole objective of a wireless sensor network. A possible solution is to equip a few sensors with GPS and design efficient algorithms to estimate the position of other sensors using range and bearing information between neighboring nodes [2] [3] [4]. However, this option will not work in such environments since GPS receivers cannot reliably operate in such conditions. Moreover, GPS is a costly solution for WSN localization systems. Therefore, the need for a GPS-free localization system that can efficiently satisfy the underwater requirements cannot be underestimated.

This paper is organized as follows. In Section II, an introduction to acoustic underwater sensor networks is presented. In Section III, GPS-free localization in underwater WSN is discussed. Section IV describes the architecture of the network. Section V presents the proposed localization schemes and the performance evaluation. Section VI discusses future research directions. The paper is concluded in Section VII.

## II. ACOUSTIC UUNDERWATER WIRELESS SENSOR NETWORKS

Underwater acoustic propagation depends on many factors that make designing an underwater wireless sensor network challenging. In the following, we present major factors that may impact the design process.

**a**. Bandwidth: The acoustic band underwater is limited due to absorption; most acoustic systems operate below 30 kHz. According to [5], no research or commercial system can exceed 40km × kb/s as the maximum attainable range × rate product.

**b**. Propagation Delay: The speed of RF is $3 \times 10^8$ m/s while the acoustic signal propagation speed in an underwater acoustic channel is about $1.5 \times 10^3$ m/s. The propagation delay in underwater is five orders of magnitude higher than the case with RF. The relatively low speed of sound causes multi-path propagation to stretch over time delay. It may greatly affect certain applications that require critical real-time communications.
**c**. Shadow Zones: Salinity, density and temperature variations of the water can influence acoustic communication. Temporary loss of connectivity is a major impact. This is evident in per the following formula [6]:

$$C = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016Z \quad (1)$$

where, C speed of sound (m/s)
T temperature (deg C)
S salinity (practical salinity units "psu" equivalent to parts per thousand)
Z depth (m)

**d**. Energy: Power is a major issue for underwater environment due to the extreme difficulties in recharging such batteries. Unlike terrestrial WSN, UWSN cannot use solar energy to regenerate the power of the batteries.
**e**. Failure: Underwater sensors are more likely to suffer failure due to corrosion and other natural phenomena.

**f**. Attenuation: It is the reduction in amplitude and intensity of a signal. Attenuation at distance x is given as [7]

$$A(x) = x^k a^x \quad (2)$$

where k is a spreading factor
a is frequency dependent term obtained as

$$a = 10^{(.\alpha(f))} \quad (3)$$

where $\alpha(f)$ is absorption coefficient given by Thorp's expression. The formula illustrates that attenuation is dependent on the frequency as well as distance.

### A. *Underwater vs.Terrestrial Wireless Sensor Networks*

Although WSN and Underwater Wireless Sensor Networks (UWSN) are different, mainly due to the unique characteristics of water, certain aspects of WSN still apply to UWSN. In the following, we highlight major differences that affect the use of WSN techniques and algorithms in the marine environment:

**a**. UWSN primarily use acoustic signals while RF is the choice for WSN.
**b**. While terrestrial sensor nodes are expected to become increasingly inexpensive, underwater-ready equipment tend to be more expensive. This is due in large to transceivers complexity and the increased protection required for the hardware.
**c**. UWSN generally require more power. This is because UWSN use acoustic signals and usually cover larger geographical areas. Compared to acoustic signals, RF systems consume less power.
**d**. The connection of an acoustic signal may be interrupted by special underwater situations like shadow zones. Due to this fact, underwater systems may need to compensate using more complicated recovery techniques. This will lead to overhead.
**e**. Density: In terrestrial sensor applications, like tracking systems, sensors can be deployed densely. While an underwater sensor is more expensive than its terrestrial counterpart, it costs more to deploy UWSN densely. Not only that but it is usually more challenging to deploy a dense underwater network.

In fact, the aforementioned differences present clues on the development of new generation of UWSN. It is clear that there is a need for new types of cost-effective sensors. For example, research interests on developing nano sensors have been growing. Moreover, the deployed network ought to be highly reliable, so as to avoid failure of monitoring missions due to failure of single or multiple sensors. New power control algorithms for UWSN are needed. Despite the fact that there is many power control algorithms for wireless terrestrial networks [8][9]. However, these algorithms are not suitable for UWSN due to the underwater channel characteristics and significant propagation delays. Additionally, novel network protocols are vitally important in reducing power consumption and providing reliable connections using sparse underwater sensors.

### B. *Classes of Underwater Wireless Sensor Networks*

According to [10], UWSN can be roughly classified into two broad categories:

*a. Long-Term Non-Time-Critical Aquatic Monitoring*

This class of UWSN is intended for long-time deployment where the collected data by the sensors is not real time. In this case, energy consumption is critical.

*b. Short-Term Time-Critical Aquatic Exploration*

Compared to long-term non-time-critical UWSN, this class of UWSN focuses on real-time data. Therefore, how to ensure efficient data transfer is a major issue when designing protocols for this type of networks. Unlike the long-term class, power consumption is not as critical.

Reference [11] classifies UWSN into three types: a) Static two-dimensional underwater acoustic sensor networks (UW-ASNs) which are most suitable for deep (i.e. bottom of the ocean) monitoring, b) Static three-dimensional UW-ASNs which are most suitable for ocean-column monitoring, and c) Three dimensional networks of Autonomous Underwater Vehicles (AUVs).

The main difference between the two classifications is the mobility aspect. In [10], long-term non-time-critical and short-term time-critical UWSN assume the ability of the sensors to move. Moreover, long-term and short-term do not distinguish between 2D and 3D. Obviously, there are some differences in protocol design.

In static two-dimensional underwater, all the sensors are fixed to the bottom of the ocean. The underwater sensor nodes are interconnected to one or more underwater sinks using acoustic signals. 2D UW-ASNs are commonly recommended for environmental monitoring.

Designing protocols for static three-dimensional underwater sensor networks, compared to the two-dimensional one, is relatively complex. The speed and propagation delay of acoustic signals differ according to water depth. This results in different power consumption levels depending on the depth of the sensor node. Clearly, it also complicates the design of efficient routing. Another challenge for this class of networks is to maintain the respective depth of the different sensors.

The three-dimensional networks of autonomous underwater vehicles may overlap with the long-term or short-term classes. “And one vital important design objective is to make them rely on local intelligence and less dependent on communications from online shores.” [11]

### C. Major Research Challenges in Uderwater Wireless Sensor Networks

**Power Consumption**

As mentioned, underwater sensors, unlike terrestrial sensors, cannot use solar energy to recharge their batteries. It is also challenging to physically replace these sensors. A straightforward approach to resolve this problem is to self-generate energy using the sensors. Research on generating energy using current movement has been conducted in the last few years. Nonetheless, efficient routing protocols and novel communication technologies are greatly needed.

**Communication Link**

Underwater networks are dominated by acoustic signals for the aforementioned reasons. Acoustic signals bring a lot of challenges to the research arena, especially propagation delay and high error rates. Alternatives are sincerely sought. The search for better options is ongoing. According to [12], optical signals have been used successfully for sensors communications. This opens the door for future possibilities. Yet, optical signals have their own challenges especially with power consumption and how they compare to acoustic signals.

**Distributed Localization and Time Synchronization**

Location-awareness has become an essential characteristic for many of the underwater applications. For these systems, data without associated location information might be useless. Among many of the large-scale terrestrial WSN applications, GPS can be used to provide accurate locations and time synchronization. In GPS-free terrestrial applications, other techniques are used to calculate the distance. Once the distance is known, the position information can be calculated using algorithms such as SemiDefinite Programming (SDP) [13]. In UWSN, the position information can be calculated in the same way. However, it is very challenging to determine the distance between two sensors. GPS cannot be used since the satellite signal is weak for underwater. Further discussion is found in the next Section.

**Routing Protocols**

In UWSN, protocol design is tied to energy efficiency especially for long-term monitoring applications. Actually, there are numerous terrestrial WSN energy-efficient protocols already developed. However, due to signal nature and environment factors, most of them are not feasible underwater. Further discussion can be found in [14].

## III. Localization in Underwater Wireless Sensor Netorks

### A. GPS-free Localization Schemes

Localization in wireless sensor networks can be formulated into a graph realization problem. Given a graph G = (V, E) and sets of non-negative weights, $\{d_{ij} : (i,j) \in E\}$, the goal is to compute a realization of G in the Euclidean space $R^d$ for a given low dimension d; to place the vertices of G in $R^d$ such that the Euclidean distance between every pair of adjacent vertices(i, j) equals (or bounded) by the prescribed weight $d_{ij} \in E$.

GPS may not be an optimal choice for underwater systems. Therefore, a GPS-free scheme is needed for such systems. The characteristics of an underwater environment represent the significant difference between Underwater Wireless Sensor Networks (UWSN) and its counterpart. The schemes and network protocols of terrestrial Wireless Sensor Networks (WSN) cannot be used directly on UWSN. Therefore, GPS-free schemes used for terrestrial WSN localization applications cannot be used directly.

Normally, localization schemes can be classified into two categories: range-based schemes and range-free schemes. Range-based schemes use range measurements to calculate position information. Time of Arrival (TOA) is used widely as a method of distance estimation using propagation time of different kinds of signals. "GPS is a most basic localization system of TOA" [15]. The disadvantage of GPS is that it is costly and may not be suitable for some applications. To use a GPS system, the GPS receivers require the installation of expensive and energy-demanding hardware to rigorously synchronize with at least four satellites. Nonetheless, GPS systems do not work in certain settings, such as indoor and underwater environments. This is due to the fact that satellite signals are not able to go through buildings and seawater.

Another widely used range-based scheme is Time Difference of Arrival (TDOA). "TDOA measures range information using time difference between two kinds of signals, such as Radio Frequency (RF) and ultrasound" [16]. Cricket [17] is one of the existing commercial TDOA localization systems. Compared to TOA, TDOA does not need to precisely time synchronize all nodes. However, like TOA, it still needs expensive and power consuming hardware to emit two different kinds of signals. Hence, it may not be suitable for low-power sensor network applications. In addition, the average propagation distance of ultrasound, which is around 15-25 feet, is too short to satisfy large-scale applications. This brings many limitations to deploy a real TDOA-based application.

To complement the TDOA and TOA schemes, Angle of Arrival (AOA) has been developed to provide the two schemes with more accurate range information [3]. The idea of AOA is to allow the sensor nodes to estimate the angles between neighbors. However, like TOA and TDOA, AOA still requires costly hardware to estimate the angles. It is clear that the majority of range-based schemes rely on accurate range measurements. These measurements are easily affected by background noise. Therefore, how to conquer the impacts caused by noise is currently an active area of research in WSN localization.

Compared to range-based, the range-free schemes are more suitable for cost-effective situations. "Range-free estimates the location of sensor nodes either by exploiting the radio connectivity information among neighboring nodes, or by exploiting the sensing capabilities that each sensor node possesses" [18]. In [19], a centroid algorithm is proposed. Based on the number of received beacons broadcasted by anchors, a centroid model was established to calculate the positions of target sensor nodes.

Another outstanding solution for range-free is DV-HOP [3]. This work uses hop-count, the average distance per hop at each node, to compute the approximate position for the sensor nodes. Other algorithms use offline hop-distance estimations and neighbor information exchange to improve the accuracy of the position results.

Compared to the range-based scheme, the cost of equipment is cheaper and the physical factors have less impact on these algorithms. However, the results may be crude not reflecting the exact position information. Therefore, such schemes will only fit applications that do not require critically precise accuracy.

*B. SemiDefinite Programming and Underwater Localization*

The trace of a given matrix A, denoted by Trace (A), is the sum of the entries on the main diagonal of A. We use I, e and 0 to denote the identity matrix, the vector of all ones and the vector of all zeros, whose dimensions will be clear in the context. The inner product of two vectors p and q is denoted by $\langle p,\ q \rangle$. The 2-norm of a vector x, denoted by $\|x\|$, is defined by $\sqrt{\langle x,\ x \rangle}$. A positive SemiDefinite matrix X is represented by $X \succeq 0$.

In [20], the mathematical model of the sensor localization problem is described as follows. "There are n distinct sensor points in $R^d$ whose localizations are to be determined, and other m fixed points (called anchor points) whose localizations are known as $a_1$, $a_2$,…, $a_m$. The Euclidean distance $d_{ij}$ between the *i*th and *j*th sensor points is known if (*i, j*) ∈ $N_x$, and the distance $\bar{d}_{ik}$ between the *i*th sensor and *k*th anchor point is known if (i, k) ∈ $N_a$. Usually, $N_x = \{(i,j) : \|x_i - x_j\| = d_{ij} \le rd\}$ and $N_a = \{(i,k) : \|x_i - a_k\| = \bar{d}_{ik} \le rd\}$, where rd is a fixed parameter called radio range. The network localization problem is to find vector $x_i \in R^d$ for all *i* = 1, 2,…, *n* such that

$$\begin{aligned} \|x_i - x_j\|^2 &= d_{ij}^2 \qquad \forall (i,j) \in N_x \\ \|x_i - a_k\|^2 &= \bar{d}_{ik}^2 \qquad \forall (i,k) \in N_a \end{aligned} \quad [20]$$

Unfortunately, this problem is, in general, hard to solve even for d = 1. In 2004, the relaxation model of this math model was represented by a standard Full SemiDefinite Programming (FSDP) model, which is shown in the following equation. For simplicity, d is set to 2.

$$\begin{aligned} \text{(SDP)}\quad & \text{minimize } 0 \cdot Z \\ & \text{subject to } \quad Z_{(1,2),(1,2)} = I_2 \\ & (0; e_i - e_j)(0; e_i - e_j)^T \bullet Z = d_{ij}^2, \quad \forall (i,j) \in N_x \\ & (-a_k; e_i)(-a_k; e_i)^T \bullet Z = \bar{d}_{ik}^2, \quad \forall (i,k) \in N_a \quad [20] \\ & Z \succeq 0. \end{aligned}$$

Here $I_2$ is the 2-dimensional identity matrix, 0 is a vector matrix of all zeros, and $e_i$ is the vector of all zeros except a

1 at the $i$-th position. If a solution $Z = \begin{pmatrix} I_2 & X \\ X^T & Y \end{pmatrix}$ is of rank 2, or equivalently, $Y = X^T X$, then $X = [x_1, \ldots, x_n] \in R^{2\times n}$ is a solution to the sensor network localization problem. Here, Z is a (n + 2) symmetric matrix.

But this model does not deal with the noise factor; it just gets the feasible solutions for the sensor localization problem. A noise factor based SDP model is proposed in [20].

$$
\begin{aligned}
&\min \sum e_{ij} + f_{ik} \\
&s.t.\ e_{ij} \geq (0; e_i - e_j)(0; e_i - e_j)^T \bullet Z - d_{ij}^2, && \forall (i, j) \in N_x \\
&\quad e_{ij} \geq d_{ij}^2 - (0; e_i - e_j)(0; e_i - e_j)^T \bullet Z, && \forall (i, j) \in N_x \\
&\quad f_{ik} \geq (-a_k; e_i)(-a_k; e_i)^T \bullet Z - \bar{d}_{ik}^2, && \forall (i, k) \in N_a \\
&\quad f_{ik} \geq \bar{d}_{ik}^2 - (-a_k; e_i)(-a_k; e_i)^T \bullet Z, && \forall (i, k) \in N_a \\
&\quad Z_{(1:2,1:2)} = I_2 \\
&\quad Z \succeq 0, && \forall (i,j) \in N_x
\end{aligned}
$$

Using this model, even with its worst case scenario of inaccurate results affected by noise factor, this mathematical model still generates relatively accurate distance estimations even in a noisy background.

However, the FSDP model requires very long time to resolve large-scale position problems. In this case, tracking applications and real-time systems are impossible to use this approach. Therefore, in 2006, Edge-based SemiDefinite Programming (ESDP) model has been developed to reduce time complexity of FSDP [20].

$$
\begin{aligned}
&\text{(SDP) minimize } 0 \cdot Z \\
&\qquad \text{subject to } Z_{(1,2),(1,2)} = I_2 \\
&(0; e_i - e_j)(0; e_i - e_j)^T \bullet Z = d_{ij}^2, && \forall (i, j) \in N_x \\
&(-a_k; e_i)(-a_k; e_i)^T \bullet Z = \bar{d}_{ik}^2, && \forall (i, k) \in N_a \\
&Z_{(1,2,i,j),(1,2,i,j)} \succeq 0, && \forall (i, j) \in N_x
\end{aligned}
$$

The only difference between FSDP and ESDP is the last constraint. The last constraint of ESDP only needs every four by four matrix to be a SemiDefinite matrix. On the other hand, FSDP works with a (n + 2) by (n + 2) matrix. ESDP will be much faster in resolving large-scale wireless sensor networks. Simulation results have proved this conclusion [21].

To use SDP, two types of data need to be collected. They are the accurate positions of anchors and the partial pair-wise distance measurements between some of the sensor nodes and the distances between sensor and anchor nodes.

SDP uses these two types of data to compute the position of every sensor node in the WSN. In practice, the number of anchors is at least three; however, more anchors can generate more accurate position results. Nonetheless, more anchors imply more cost. Therefore, how to deploy a limited number of anchors to generate accurate position results is a challenging issue in designing this localization system. According to [20], if all sensor nodes can connect to any anchor nodes, directly or indirectly, the solution for SDP must be bounded. Therefore, appropriate radio range should be adjusted depending on different situations in order to make sure all sensor nodes can connect to at least one anchor directly or indirectly.

In [20], it is mentioned that various techniques have been developed to address measurement uncertainties. Most of these methods are based on minimizing some global error functions, which can be different depending on the model of uncertainty. According to the type of optimization model being formulated, the characteristics and computation complexity vary. “Existing algorithms have limited success, even for small problem sizes” [22]. Moreover, in the real world, all the distance measurements inevitably have noises. Using this noisy distance information, we cannot get satisfactory results. However, SDP had been proved that it could generate accurate results even in extremely noisy backgrounds. More importantly, there is no special node(s) in the SDP approach. Hence, even if some of the nodes were destroyed, the localization system will still work and continue to generate relatively accurate results.

In [21], two future relaxations of SDP, NSDP and ESDP, have been proposed and tested. The performance of SDP approach and ESDP approach can be found in [13][21]. Further details and complete discussions on SDP can be found in [13][20][21].

### *C. Motivation*

Recently, marine biology research has increasing needs of using the position information, especially in migration and distribution research such as red king crabs research. Most research is based on ship data collection. Biologists need to be sailing across the area utilizing a data receiver to collect data. This is very expensive and has many limitations, such as meteorological factors. Therefore, it is more convenient, if the biologists can get the data onshore, significantly reducing the cost of research. Migration and distribution research belong to a long-term non-time-critical research, normally at least one year. The design for this kind of system needs to focus on low energy consumption and stable communication. In this paper we propose a SemiDefinite Programming underwater localization system, which provides biologists with a convenient and cheaper way to collect data in marine research.

## IV. Network Architecture

It is needed to collect anchors' position coordinates and the partial pair-wise distance measurements between the nodes for the proper operation of SDP-based localization systems. Partial pair-wise distances include the distances between sensors, and distances between anchors and sensors. SDP uses the collected data to compute the position of every sensor node. According to [13], three factors impact the accuracy of results from the SDP approach. The factors are the number of anchors, connectivity (number of reachable sensors in a sensor acoustic range), and background noise. More anchors, large connectivity and less noise lead to better accuracy and accurate position results. Among these three factors, it is possible to control the first two factors, but it is challenging to deal with the noise factor. Despite the performance gain, increasing the number of anchors and improving connectivity increase the cost of the system. Therefore, a balance between the result accuracy and cost needs to be weighed carefully.

The design of UWSN architecture needs to address three key problems to satisfy the requirements of SDP. First, how do anchor nodes get their position coordinates? This issue is a common challenge to a wide array of UWSN applications. Second is how to calculate pair-wise accurate distances between sensor nodes. Third is how to improve the connectivity of the system. The solution to the first problem is floating sensors. These nodes float on the water surface and have the ability to communicate using radio frequency (RF) and acoustic signals. These sensors may be utilized as anchor nodes. RF can be used for above-water communications including exchanging GPS information with other floating/anchor nodes and onshore base stations. The acoustic signal is used for communicating to the underwater sensor nodes. Therefore, floating sensors may act as sink nodes.

To resolve the second problem, round trip propagation of data packets is used to measure the distance between two sensor nodes. When underwater sensors are activated, they send distance-measure packets. If a neighbor within acoustic signal range gets the data packet, this neighbor sends a reply packet to the original sender node. The reply includes an arrival time stamp for the distance-measure packet. Also, it includes the depth, temperature and salinity data of the neighbor nodes. Then the data package is sent by the original sensor node to floating sensor nodes. During this process, the original sensor node adds its own depth, temperature and salinity data to the package. Finally, the collected data can be relayed to a base station for further distance calculations. The depth, temperature and salinity information is used to calculate the speed of the acoustic signal. Round-Trip Time is the total time from sending the distance-measure packet to receiving a reply. Therefore, the distance between a sensor node and its neighbor can be calculated as *speed of sound * Round-Trip-Time / 2*. However, there are underwater factors that can affect the round trip measurement consistency. Therefore, multiple group measurements are to be collected before transmitting to the floating sensor node. Standard deviation should be used to justify whether those samples in the group are accurate. If not, next group measurements will be tested until the smallest standard deviation group is found.

As stated earlier, connectivity is a major factor in achieving high accuracy. However, in certain applications such as tracking king crabs, there is no guarantee for enough sensors surrounding a target node to provide strong connectivity. Therefore, another type of sensors may be used for such systems; *Fixed-Position scheme*. The main idea is to improve connectivity of the whole system. Compared to other sensors, fixed-position nodes will not move with the target. Although the name is "fixed," it does not mean they are anchored at a certain position. In real applications, they can move within a certain area which will be defined in advance. They are deployed to evenly cover the monitored area and measure temperature, depth and salinity for calculating the speed of the acoustic signal. However, if the applications need to monitor the area in addition to tracking the target, those transmitter nodes are equipped with necessary sensors to measure other environment phenomena. The design of Fixed-Position scheme provides other benefits. Most importantly, it leads to a reduction in power consumption for all sensor nodes. This is because node connectivity must be above a certain level to guarantee the accuracy of position results. If the system does not have these transmitters, it should increase the power of acoustic signal to improve coverage range. In this case, all sensors will be subject to extra power consumption in order to complete the task.

The straightforward solution, to increase connectivity, is to increase all sensors' acoustic range. However, as mentioned above, this will lead to highly increased power consumption. Thus, it will reduce the system's lifetime. Since the power of floating anchors can be recharged, it is possible to only magnify the anchors' acoustic signal range (i.e. *Magnified-Range Scheme*). In this case, all regular sensor nodes will have the opportunity to connect to anchors directly or indirectly. Hence, magnified anchors' signal range will improve the probability to achieve more accurate results. A network architecture is illustrated in Figure 1.

## V. Simulation and Performance Analysis

All simulations are based on a 2-D domain and all tests are solved by SeDuMi 1.1 of MatLab2007b on a MacBook Pro laptop with 2.16GHz Intel Core 2 Duo CPU, 2 GB 667 Mhz DDR2 Memory. In this simulation, we randomly generate the true position of all sensor locations in a square of 1 by 1.

To prove that the three factors, namely anchor number, connectivity and noise factor, significantly affect position results reported by the SDP approach, numerous simulations have been performed in [13][20][21][23]. The purpose of our simulation is to show that our proposed schemes are effective and achieve accurate localization. Moreover, issues in regard to how to deploy anchors in real applications will be discussed.

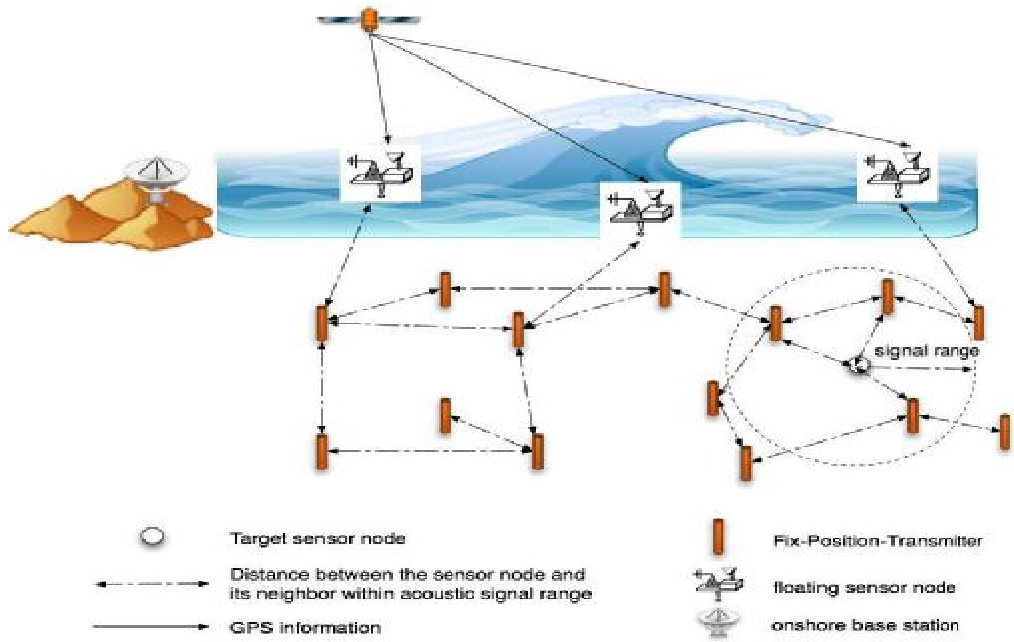


Figure 1. Network Architecture.

### *A. Error Estimations*

In these simulations, three methods are used to estimate errors namely a) Error, b) Root Mean Square Deviation (RMSD) and c) Individual Trace. These errors often occur in real applications either due to the lack of information or the presence of noise, and are often difficult to detect since the true locations of sensors are unknown.

- **Error:** It is the distance between each pair of true position and estimate position. In these simulation settings and unlike real-life applications, it is possible to compare the true and estimate positions.

- **Root Mean Square Deviation (RMSD):** It measures the accuracy of the estimated positions $\{x_i : I = 1, \ldots, n\}$. The formula is shown below. This method cannot be used in real-life applications since the true positions of the sensor nodes are unknown. This metric is only useful for simulation purposes. Lower RMSD means the global error is smaller.

$$RMSD = \frac{1}{\sqrt{n}}\left(\sum_{i=1}^{n}\left\|\bar{x}_i - x_i\right\|^2\right)^{1/2} \qquad (4)$$

where, n is number of target sensor nodes
$x_i$ is the true position of ith sensor nodes
$x_i$ is the estimated position of ith sensor nodes.

- **Individual Trace:** When relaxing to the SDP model, change $Y = X^T X$ to $Y \succeq X^T X$. This is equivalent to $Z = \begin{pmatrix} I & X \\ X^T & Y \end{pmatrix} \succeq 0$. Thus, $Y - X^T X$ represents the co-variance matrix of $x_i$, i = 1, …, n. Individual trace $Y_{ii} - \|x_i\|^2$,Which is also the variance of $\|x_i\|$. This helps detecting possible distance measure errors, and defect sensors in real application [13].

In the following, two kinds of chart are illustrated; position simulation charts and error estimation charts, respectively. In position simulation charts, the **red squares** indicate the position of anchors. The **green circles** present the true position of target sensor nodes. The **blue asterisks** show the estimated position of the target sensor nodes. The **blue lines** between green circles and blue asterisks represent the distance between true positions and estimated positions. In error estimation charts, the **red squares** represent the individual trace. The **blue circles** refer to errors.

### *B. Fixed-Position Scheme Simulation*

**Purpose**: To test the Fixed-Position theory.

**Analysis**: Figure 2 shows the estimated results using 3 anchors, 30 sensor nodes and signal range of 0.3. It is clear that the results are very inaccurate. Instead of using a larger signal range to increase connectivity, we deploy 10 more sensor nodes in the area. The results are shown in Figure 3. Compared to Figure 2, the estimated results are much more accurate. The results in Figure 3 show a reduction in the global error from 0.162 to 0.039.

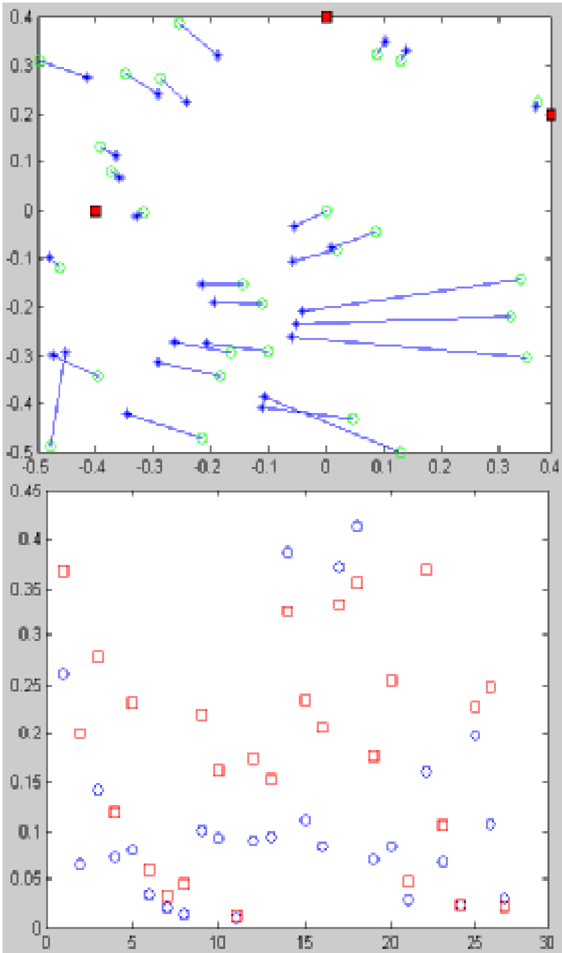

Figure 2. Fixed-Position Simulation 1 (RMSD = 0.162)
Condition: Anchor Number = 3; Sensor Number = 30; Acoustic Range = 0.3

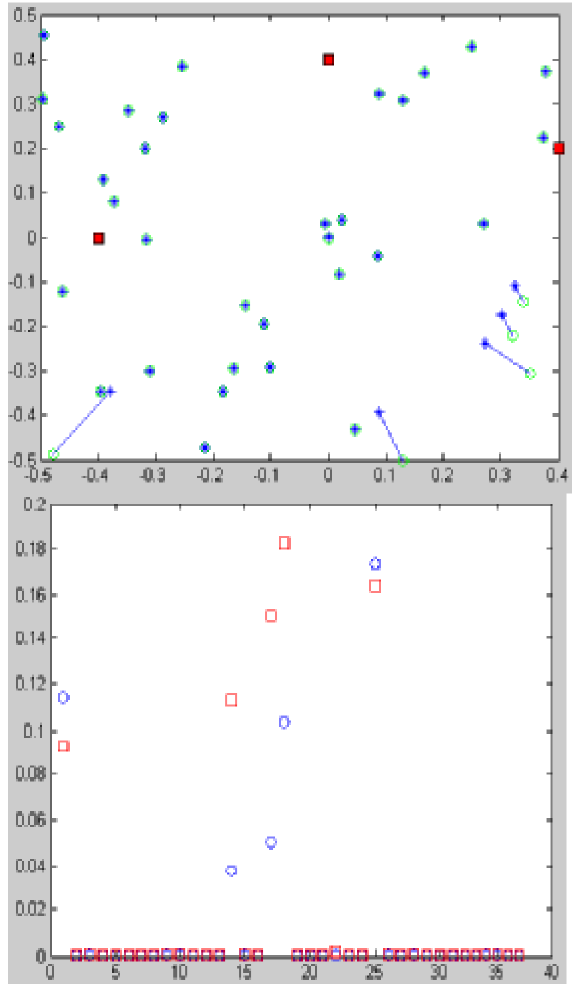

Figure 3. Fixed-Position Simulation 2 (RMSD = 0.039)
Condition: Anchor Number = 3; Sensor Number = 40; Acoustic Range = 0.3

### *C. Magnified-Range Scheme Simulation*

**Purpose**: to test the performance of magnified-range theory.

**Analysis**: The difference between this simulation and the previous one is that the noise factor is set to 0.05. This is why the overall accuracy is lower than the results in Figure 3. The simulation in Figure 4 uses the same signal range for both; sensor nodes and anchors. While the simulation in Figure 5 uses 0.3 for the sensor signal range and 0.5 as anchor signal range. The simulation results show that the configuration in Figure 5 with magnified signal range improves the accuracy by around 20% compared to Figure 4.

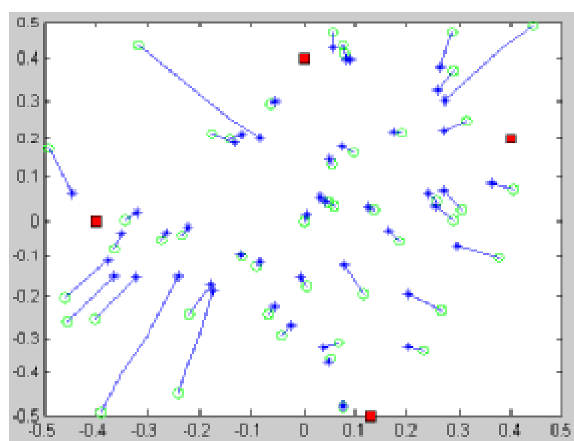

Figure 4. Magnified-Range Simulation (RMSD = 0.124)
Condition: Anchor Number= 4; Senor Number = 50; Noise Factor = 0.05; Senor Signal Range = 0.3

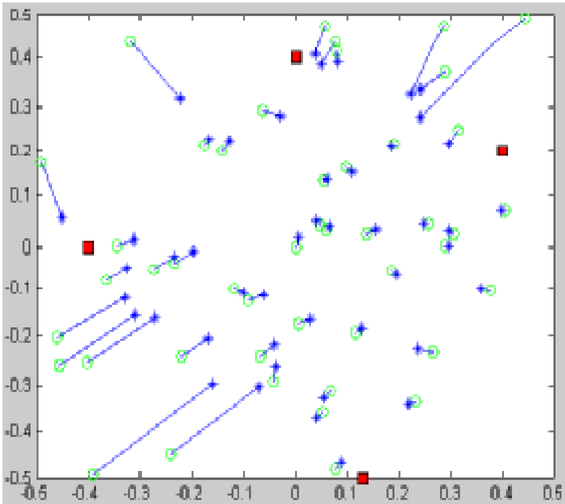


Figure 5. Magnified-Range Simulation (RMSD = 0.098)
Condition: Anchor Number = 4; Senor Number = 50; Noise Factor = 0.05; Anchor Signal Range = 0.3 and 0.5

## VI. FUTURE WORK

The simulations are currently based on 2-D environment to test the performance of our proposed schemes. Real applications may require 3-D environments. Therefore, our next research step is to focus on 3-D simulations. Moreover, the following challenges will be further investigated.

First, how to get more accurate distances between sensor nodes? Due to the limitations of acoustic signals and unique characteristics of underwater environments, it is very hard to compute the accurate distance. However, if it is possible to provide more accurate distance using other measurement schemes, it guarantees a better performance for the SDP approach. Moreover, this will allow the use of other localization schemes, especially some terrestrial range-based localization scheme.

Second, energy-efficient routing protocols are needed in such settings. Underwater routing protocols are relatively a new field. The unique features of acoustic propagation and noise make most of terrestrial WSN routing protocols not suitable for UWSN. Therefore, we plan to investigate the design of energy-efficient routing protocols that fit the marine environment especially in discovering the neighboring nodes within signal range.

Third is combining other localization approaches with SDP. There are many localization schemes that may lead to a better performance if combined with SDP. Therefore, we plan to research existing approaches to find a possible way to combine with our SDP-based schemes. This will probably lead to a hybrid localization scheme. The new system should generate better results and should address more marine applications and research problems.

Fourth, real-life experiments will be conducted. We plan to use commercial underwater transmitters to test our architecture design and schemes. Real-life demonstrations are most likely to reveal insights on improving the design and performance of the system. In fact, we are gathering more information on water current, attacks from sea creatures and other natural factors. This should help design a more robust underwater localization system.

## VII. CONCLUSIONS

Compared to other localization algorithms, the SemiDefinite Programming (SDP) approach is proved to deliver accurate results even in noisy backgrounds. In this paper, we propose a design for underwater localization systems using SemiDefinite Programming. The objective is to provide marine scientists with a cost-effective and efficient way for conducting relevant research. Two designs, Fixed-Position and Magnified-Range, are proposed. Both schemes have shown better accuracy and performance, according to simulation results, over conventional networks. Future research directions are discussed in this paper.

## ACKNOWLEDGMENT

This work was supported, in part, by an NSF CRI grant and a Texas Research Development Fund grant.

## REFERENCES

[1] B. Dong, and A.M. Mahdy, “GPS-Free Localization Schemes for Underwater Wireless Sensor Networks,” Proceedings of the Third International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies, 2009, pp. 244-248.
[2] Y. Shang, W. Ruml, Y. Zhang, and M.P.J. Fromherz, “Localization from Mere Connectivity,” Proc. of ACM MobiHoc, Annapolis, MD, 2003, pp. 201- 212.
[3] D. Niculescu, and B. Nath, “Ad Hoc Positioning System (APS) Using AOA,” Proceedings of IEEE INFOCOM, San Francisco, CA, USA, 2003.
[4] A. Savvides, C.C. Han, and M. Srivastava, “Dynamic fine-grained localization in ad hoc networks of sensors,” Proceedings of MobiCom, 2001.
[5] D.B. Kifoyle, and A.B. Baggeroer, “The State of the Art in Underwater Acoustic Telemetry,” IEEE Journal on Oceanic Engineering, OE-25, No. 5, 2000, pp. 4-27.
[6] P.C. Etter, “Underwater Acoustic Modeling, Principles, Techniques and Application,.” 2nd edition, E&FN Spon, 1996.
[7] L. Berkhovskikh, and Y. Lysanov, “Fundamentals of Ocean Acoustics,” Springer, 1982.
[8] J. Proakis, J. Rice, E. Sozer, and M. Stojanovic, “Shallow water acoustic networks,” Encyclopedia of Telecommunications, John Wiley and Sons, 2003.
[9] V.O. Knudsen, R.S. Alford, J.W. Emling, “Digital Communications,” Journal of Marine Research, (7-12):410, 1948.
[10] J.H., Cui, J. Kong, M. Gerla, and S. Zhou, “The Challenges of Building Scalable Mobile Underwater Wireless Sensor Networks for Aquatic Applications,” IEEE Network, (0890-8044), 2006, pp. 12-17.

[11] I.F. Akyildiz, D. Pompili, and T. Melodia, “Underwater Acoustic Sensor Networks: Research Challenges,” Elsevier Ad Hoc Networks, Vol. 3, No. 3, 2005, pp. 257-279.
[12] I. Vasilescu, K. Kotay, and D. Rus, “Krill: An Exploration in Underwater Sensor Networks,” Proceedings of the Second IEEE Workshop on Embedded Networked Sensors, 2005, pp. 151-152.
[13] P. Biswas, and Y.Y. Ye, “Semidefinite programming for ad hoc wireless sensor network localization,” Proceedings of the third international symposium on Information Processing in Sensor Networks, 2004, pp. 46-54.
[14] B. Dong, and A.M. Mahdy, “A Survey of Underwater Wireless Sensor Networks,” Journal of Computing Sciences in Colleges, Electronic Issue, 2008.
[15] B.H. Wellenhoff, H. Lichtenegger, and J. Collins, “Global Positions System: Theory and Practice,” Fourth Edition. Springer Verlag, 1997.
[16] P. Bahl, and V. Padmanabhan, “RADAR: An In-Building RF-based User Location and Tracking System”, Proceedings of IEEE INFOCOM, 2000, pp. 775-784.
[17] CrossBow, Available from www.xbow.com (last visited June 2010).
[18] R. Stoleru, T. He, and J.A. Stankovic, “Secure Localization and Time synchronization for Wireless Sensor and Ad Hoc Networks,” Springer, 2007.
[19] N. Bulusu, and D. Estrin, “GPS-less Low Cost Outdoor Localization for Very Small Devices” IEEE Personal Communications Magazine, 7(5), pp. 28-34.
[20] P. Biswas, C. Liang, C. Wang, Y.Y. Ye, “Semidefinite programming based algorithms for sensor network localization”, ACM New York, NY, USA, May 2006, pp.188- 220.
[21] Z. Wang, S. Zheng, Y.Y. Ye, and S. Boyd, “Further Relaxations of the Semidefinite Programming Approach to Sensor Network Localization,” SIAM Journal on Optimization, Vol 19, Issue 2, 2006, pp. 655-673.
[22] J.J. More, and Z. Wu, “Global continuation for distance geometry problems,” SIAM Journal on Optimization, Vol 7, Issue 3, 1997, pp. 814-836.
[23] A.M.-C. So and Y. Ye, “Theory of semidefinite programming relaxation for sensor network localization”, Proceedings of the sixteenth annual ACM-SIAM symposium on Discrete algorithms, 2005, pp. 405-414.