Error Tolerant Dual-Hydrophone Localization in Underwater Sensor Networks

Sanfeng Zhu, Naigao Jin, Lei Wang, Shuailing Yang, Xueshu Zheng, Ming Zhu, Liang Sun
Key Laboratory for Ubiquitous Network and Service Software of Liaoning Province
School of Software, Dalian University of Technology, China
{sanfeng.zhu, yangsl1008, xueshuzheng.steve, liang.sunry}@gmail.com, {ngjin, lei.wang, zhuming}@dlut.edu.cn

***Abstract*—In this paper, we propose an Error Tolerant Dual-Hydrophone Localization method, i.e., ET-DHL, in underwater sensor networks (USNs). To reduce the impact of the node uncertainty, measurement uncertainty, poor link quality and long latency for underwater localization problem, ET-DHL adds bit-level probability to process the binary sequence. Different from our previous work PCM, each dual-hydrophone node in ET-DHL leverages different probabilities based on TDOA to distinguish which half-plane the source lies in, and ET-DHL takes the sum of expectations of all small regions by normalizing all weighted probability to localize the source. The proposed design is evaluated through extensive simulations, evaluation results demonstrate that ET-DHL can effectively locate the acoustic source with good robustness for node location error, node angle error and measurement uncertainty.**

***Index Terms*—Underwater Sensor Networks, Error Tolerant Localization, Probability, Half-plane Intersection**

I. Introduction

During last couple of years, we could observe a growing interest in USNs, USNs provides new opportunities to explore the oceans, and consequently it improves our understanding of the environmental issues, such as the climate change, the life of ocean animals and the variations in the population of coral reefs. Among all research studies, localization has been addressed widely in underwater acoustic sensor networks, underwater localization can be used in many occasions, such as underwater rescue [1], locating a target in underwater [2], and locating an autonomous underwater vehicle (AUV) [3].

Localization for UWSNs has been one of the major research tracks, different from the terrestrial environment, underwater acoustic channels are characterized by harsh physical layer conditions with low bandwidth, large Doppler spread, high propagation delay, high delay variance and high bit error rate. Moreover, The sound speed variation with depth in the water environmentcould affect localization accuracy.

In this paper, we design a dual-hydrophone sensor network to reduce low link quality and sensor node mobility challenges. The proposed ET-DHL system has following advantages: (i) Remove time synchronization requirement: The pairwise hydrophones in each node are synchronized, and ET-DHL uses the sign of TDOA (Time Difference of Arrival) of each node as the measurement data to reduce time synchronization requirement between nodes. (ii) Reduce multi-path interference: Due to dual-hydrophone is close to each other, the impact of multi-path effect on localization is not obvious. (iii) Error tolerant localization: Binary left/right data is a kind of robust measurement, and different probabilities based on TDOA for half-plane intersections provide more robustness to the impact of node location error, node angle error and fault nodes. (iv) Low communication overhead: The poor link quality of USNs results in frequently retransmission of packages. ET-DHL passes 1 bit binary information and TDOA information in USNs to lower the communication overhead.

The rest of this paper is organized as follows. In Section II, we review some related work. Section III presents the preliminary system overview. Section IV shows the details of the system design. The simulation of the system is evaluated in Section V. Finally, Section VI summarizes the conclusions.

II. Related Work

Localization has been widely studied in the USN, context and detailed surveys of these techniques have been presented in [4] and [5]. In the literature, underwater acoustic localization can be broadly classified into two categories: range-based and range free. Range-based localization techniques typically comprise three steps: (i) Range measurement. Each node estimates its distance from the unknown node using Received signal strength indicator (RSSI) [6], Time difference of arrival (TDOA) [7], Time of arrival (TOA) [8]. (ii) Localization estimation. Applying triangulation or multi-lateration to transform ranges into coordinates. (iii) Calibration. The location estimation is refined by using measurements from various iterations,measurement error models, mobility models. Range-free techniques explore the local topology and derive the position estimation from the locations of the surrounding anchor nodes, such as 3D-MALS [9] and LDB [10]. Generally speaking, range-based schemes provide much more higher localization accuracy, whereas range-free schemes provide coarser location estimation.

In [11], a large-scale hierarchical localization (LSHL) is proposed for USNs. Cheng *et al.* [12] propose an underwater positioning system (UPS), which uses TDOA techniques by multiple beacon intervals, thus UPS requires no time synchronization and provides location privacy at underwater vehicles/sensors whose locations need to be determined. As our previous work, we propose a probability-based acoustic source localization scheme using dual-microphone smartphones, named PCM [13], to convert the localization problem

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into probability-based plane cutting issues, but PCM gives all nodes the same probability based on SNR to cut the plane and do not use the value of TDOA which carries a lot of information for localization, moreover, it takes the center of the peak of the maximum weighted region as the source's location. To explore the idea of using dual-microphone sensors to localization the source, we come up with a novel dual-hydrophone localization method termed DHL [14] in underwater sensor networks, it adds an empty set detection to solve the empty set problem and locate the acoustic source using half-plane intersections. Zhang *et al.* [15] propose a weighted Hamming distance ranking algorithm (WhRank) to rank the binary codes of hashing methods by assigning different bit-level weights to different hash bits. For further study, we present an error tolerant dual-hydrophone localization method called ET-DHL to locate the acoustic source in USNs for this paper. ET-DHL gives different bit with different probability based on TDOA to judge which half-plane the source locates in, to locate the source, ET-DHL normalizes weighted probabilities of all small regions, and takes the location of the sum of expectations of all small regions as the estimated location of the target.

III. System Overview

In this section, we present the system overview of our system. Fig. 1 shows the layout of our system formed by three different types of nodes.

- Surface buoys. Each surface buoy serves as the "satellite node" in USNs, and it is equipped with common GPS (Global Positioning System) and IMU (Inertial Measurement Unit), so each surface buoy can get its absolute position from the GPS and direction from IMU. When the surface buoy receives the sensed data, it passes the data to the server in the station by RF signal, then the server analyses the data to localize the acoustic source.
- Dual-hydrophone nodes. There are some sensor nodes armed with two hydrophones in our USNs, and the distance between the two hydrophones on one node is fixed. Each dual-hydrophone node is attached to a surface buoy by a cable, and each dual-hydrophone node can get its direction and position by communicating with its surface buoy through the cable. When one dual-hydrophone node senses signal emitted by the source, the node computes the TDOA from the source to the its dual-hydrophone.
- The acoustic source. There exists one acoustic source in our system, and it can emit a beep periodically. The goal of our work is to locate the dominant acoustic source by processing the binary sequence with probability.

IV. System Design

In this section, we mainly focus on the system design of our method ET-DHL (Error Tolerant Dual-Hydrophone Localization). With the dual-hydrophone nodes, ET-DHL uses the sign of TDOAs as the binary measurement information, and gives each node an unique probability to judge which region the acoustic source belongs to. The key idea of ET-DHL is to turn the localization problem into bit-level probabilistic half-plane intersection by processing the binary sequence.

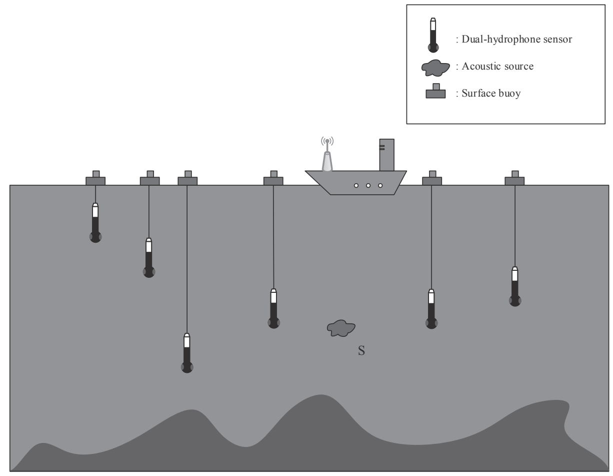
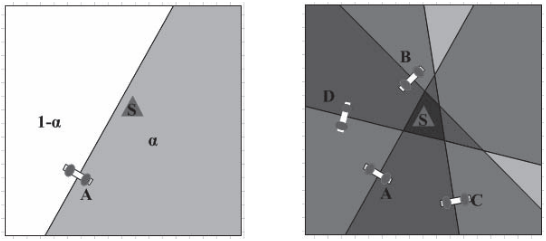


Fig. 1. System overview. An underwater sensor network formed by dual-hydrophone sensors to locate the acoustic source.

A. Probabilistic Half-Plane Decision

As mentioned in our previous work [14], we proposed an novel dual-hydrophone localization method called DHL. To make it easy to understand, we use 2D case to describe the process of DHL. As shown in Fig. 2(a), the whole space can be divided into two half-planes marked with different color by the perpendicular bisector of node A's dual-hydrophone, if there exists N nodes in the space, the space can be devided into $2N$ half-planes. When A hears the sound from the acoustic source S, it computes TDOA from S to its dual-hydrophone, and the sign of TDOA can decide the half-plane which the acoustic source belongs to. If the sign of TDOA is positive, then we marked the corresponding region with binary code 1, so the opposite region is 0. After using all nodes in the space to decide regions contain the source, the server will get a binary sequence $BinSequence$. After processing the $BinSequence$ using half-plane intersections, DHL can narrow the final region of the source, and take the center of the final region to get the estimated location. DHL adds an empty set detection process to reduce the localization failure caused by uncertainty of node locations and uncertainty of node orientations, whereas, fault nodes in the space pass error information to the server to influence the localization result, which DHL can not solve. In order to deal with the empty set problem and error information, we leverage bit-level probabilistic half-plane intersection to improve the robustness of localization system in ET-DHL.

Different from DHL, each dual-hydrophone node in ET-DHL passes node location, node direction, binary information along with TDOA information to the server, then the server analyzes all the information to locate the target. In most binary algorithms, each bit takes the same weight and makes the same contribution to distance calculation. On the contrary, in our algorithm, we give different bits different weights according



(a) (b)

Fig. 2. Basic idea of ET-DHL.

to the value of TDOA. As shown in Fig. 2(a), if the probability of the half-plane including the acoustic source is α, then the probability of the other half-plane is $1-\alpha$, thus we have

$$p(i) = \begin{cases} \alpha & \text{if} \quad BinSequence(i) = 1, \\ 1-\alpha & \text{if} \quad BinSequence(i) = 0. \end{cases} \tag{1}$$

where α is the probability related to the TDOA of each node.

B. Probability Decision

After the server receives the location information, direction information and measurement information of all nodes, it decides the probability for detecting the credibility of the 0/1 information based on all the value of TDOA. According the definition of probability, $\alpha \in [0, 1]$. For the probabilistic theory in our algorithm, the result of binary information is 0/1, so if $\alpha < 0.5$, we will get more imprecise estimated result. Thus $\alpha \geq 0.5$ should be guaranteed to ET-DHL, thus $\alpha \in [0.5, 1]$. If the value of TDOA is smaller, the source is close to the perpendicular plane of the two hydrophones on the node, otherwise, it is far away from the perpendicular plane of the two hydrophones on the node, so the smaller the TDOA is, the more credible it is. The server analyzes all the value of TDOA, and chooses the maximum value of TDOA represented by T_{max} and T_{min} as the minimum value of TDOA, and gives bigger probability for the node with T_{min}. We define a function to get the bit-level probability as

$$\alpha = \alpha_{max} + (\alpha_{min} - \alpha_{max}) sin(\frac{\pi * (T_i - T_{min})}{2 * (T_{max} - T_{min})}) \tag{2}$$

where T_i is the TDOA of $i-th$ node, α_{max} denotes as the maximum probability choose for all nodes, and α_{min} is the lower bound of the probabilies.

C. Location Estimation

After assigning each node a bit-level probability, ET-DHL processes the binary sequence using half-plane intersections, and we can get K small regions with different weighted probabilities shown in Fig. 2(b). The weight w of each region is defined as the product of probability of $2N$ half-planes

$$w(k) = \prod_{i=1}^{N} p(i), k = 1, \cdots, K \tag{3}$$

The location of the acoustic source is estimated as

$$\hat{X} = \sum_{k=1}^{K} R(k) \hat{w}(k), \tag{4}$$

where $R(k)$ is the central point of the region k, and $\hat{w}(k)$ is normlized weight

$$\hat{w}(k) = w(k) / \sum_{k=1}^{K} w(k). \tag{5}$$

To summarize, ET-DHL is presented in Algorithm 1. The input are the location coordinates, direction, the output is the estimated location of the acoustic source.

Algorithm 1: The ET-DHL Algorithm

Input: The location coordinates of nodes
The direction of nodes
Output: Estimated location: $\hat{X}$

for *node* $i \leftarrow 1$ ***to*** N **do**
  Using i's direction and location to get $TDOA(i)$;
  Taking *sign($TDOA(i)$)* to get $BinSequence(i)$;
  Passing $BinSequence(i)$ to the server.
end
for *node* $i \leftarrow 1$ ***to*** N **do**
  Getting the bit-level probability: (2);
  Processing the binary sequence using half-plane intersection;
end
Obtaining weighted probability for each small region: (3);
Normalizing the weighted probability: (5);
Computing the estimated location: (4).

V. Simulation

In this section, we evaluate the performance of ET-DHL with the impact of node number, error nodes, node location error and angle error on localization error using MATLAB. In our simulation, 100 dual-hydrophone nodes are randomly deployed in a 100 × 100× 100m area. We choose $\alpha \in [0.5, 1]$ as the probability for processing each bit based on TDOA in the binary sequence, and the distance between the dual-hydrophone on each node is 0.5m. To simulate the impact of the uncertainty of position and orientation of nodes on the accuracy of localization, we add a zero-mean with 0.5 variance node location error, and a zero-mean with 10 variance node angle error. All the statistics are running 500 times for high confidence, and reported by CDF figure.

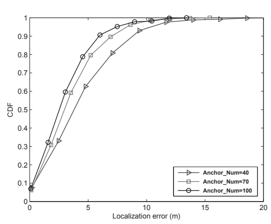
1) Impact of the number of nodes: In this simulation, we investigate ET-DHL with the effect of different node number on localization error, all the other parameters keep default. Fig. 3(a) shows relationships between localization error and CDF with 40, 70 and 100 nodes for ET-DHL. As shown in

Fig. 3(a), with node number increases, the localization error decreases, because the localization space can be divided into many small regions as the node number increases, and about 95% of localization error below 7m for 100 nodes.

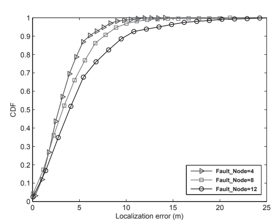
2) Impact of fault nodes: We simulate ET-DHL with the impcat of fault nodes on localization error, other parameters remain default. Fig. 3(b) shows the localization results of 4, 8 and 12 fault nodes, and it indicates that the localization error increases as the number of error nodes increases for ET-DHL. It shows although it appears error nodes, more than 88% of localization error within 9m for the three curves, which means ET-DHL has error tolerance ability.

3) Impact of node angle error: We conduct the simulation with the impact of node angle error on localization error for ET-DHL. And we choose 15°, 25°, 35° to show the localization error and CDF in Fig. 3(c). As shown in Fig. 3(c), the localization error for ET-DHL increases as node angle error increases, and about 97% of localization error is below 10m when there exists 15° node angle error.

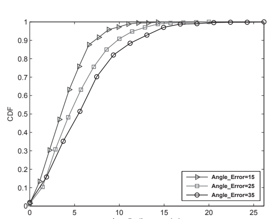
4) Impact of node location error: We evaluate ET-DHL with the effect of node location error on localization error from 0m to 5m, other parameters remain default. Fig. 3(d) shows the relationships between localization error and CDF of 0.5m, 1.0m and 1.5m node location error. It indicates that the location error of nodes can affect the localization results. As demonstrated in Fig. 3(d), nearly 90% within 6m localization error for the three curves.



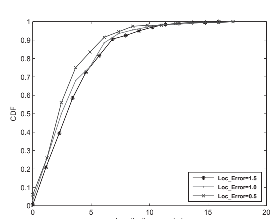
(a) Impact of the number of nodes.



(b) Impact of fault nodes.



(c) Impact of node angle error.



(d) Impact of node location error.

Fig. 3. Simulation results for ET-DHL.

VI. Conclusions

In this paper, we present ET-DHL, an Error Tolerant Dual-Hydrophone Localization in underwater sensor networks to locate an unknown acoustic source. ET-DHL uses the sign of TDOA to get binary sequence, and gives each bit different probability. By processing the binary sequence of nodes, we can convert the localization problem into probabilistic half-plane intersection issues. Simulation results demonstrate that ET-DHL has high fault tolerance when node angle error, node location error and fault nodes exist.

Acknowledgments

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