MobiL: A 3-Dimensional Localization Scheme for Mobile Underwater Sensor Networks

Tamoghna Ojha
School of Information Technology
Indian Institute of Technology Kharagpur
Kharagpur 721302, India
Email: tojha@sit.iitkgp.ernet.in

Sudip Misra
School of Information Technology
Indian Institute of Technology Kharagpur
Kharagpur 721302, India
Email: smisra@sit.iitkgp.ernet.in

***Abstract*—In this paper, we introduce a 3-dimensional, distributed, iterative, and 'silent' localization protocol for Mobile Underwater Sensor Networks (MUSNs) named as Mobility Assisted Localization Scheme (MobiL). The existing solutions addressing the localization problem in underwater sensor networks (UWSNs) either consider the sensor nodes to be stationary or require powerful nodes, which can directly communicate with the surface sinks. Such assumptions are not applicable in MUSNs, where sensor nodes are affected by passive node mobility and the acoustic communication channel is severely impaired by high propagation loss. On the other hand, MobiL requires only three anchor nodes capable of providing the initial location beacon and all other nodes are ordinary sensor nodes. We exploit the spatially correlated mobility pattern of UWSNs and apply it to localize the sensor nodes. Also, we employ the 'silent' listening of beacon messages, which empowers MobiL to be energy-efficient. Simulations in NS-3 show that the proposed scheme successfully localizes nearly 90% of the total sensor nodes with localization error in the order of 25-30% of the error threshold in highly mobile UWSNs.**

***Index Terms*—Silent localization, Underwater Sensor Networks, Node mobility**

I. Introduction

Localization is an essential requirement for MUSN applications such as target tracking, disaster prevention, environmental monitoring, and surveillance [1], [2]. It is also a requirement for the geographical routing protocols [3]. In MUSNs, sensor nodes cannot remain fixed at a position with the effect of passive node mobility [4]. Other UWSN challenges [5] such as acoustic communication, high attenuation of signals, limited battery power, and variable propagation delay, are also relevant in MUSNs. The use of acoustic signal instead of radio frequency as the communication medium, limits the transmission range of sensor nodes. Also, the propagation delay increases as acoustic signal speed (1500 m/s) is five orders of magnitude less than the radio frequency propagation speed (3×10^8 m/s).

Due to the high attenuation of radio signal, GPS-based localization schemes do not work in MUSNs. Also, being resource hungry, GPS drains the battery power of a sensor node quite rapidly. The localization coverage of Autonomous Underwater Vehicle (AUV) based schemes largely depend on the AUV trajectory, and at the same time, the use of AUVs introduce additional cost to network implementation. Besides, some localization protocols assume a powerful node, which acts as anchor and aids the localization process of ordinary sensor nodes by communicating with the surface buoys directly. This is also an unrealistic assumption considering the high power consumption using acoustic modems for such long distance. Therefore, to achieve network wide localization coverage in a MUSN, it is pertinent to rely on the iterative localization schemes.

The iterative localization schemes determine the location of an unknown node by means of message passing between such nodes and anchor nodes. The messaging is 'active' when both the unlocalized and anchor nodes participate in message sending. In 'silent' messaging, the anchor nodes send beacon messages, and the unlocalized nodes silently listen to them. Therefore, 'silent' messaging is much energy-efficient than the 'active' scheme.

In this paper, we introduce an iterative localization scheme, named MobiL, for 3-dimensional MUSNs. In MobiL, a sensor node is able to calculate its displacement between the reception of three beacon messages from anchors. For this calculation, we exploit the spatially correlated mobility pattern of underwater sensor nodes. Therefore, the proposed scheme is accurate in determining the location of an unknown sensor node. Initially, three surface deployed anchor nodes provide the beacon messages for localization. The underwater nodes once localized act as anchors for the unlocalized nodes. Also, the sensor nodes localize themselves by listening to only three beacons 'silently', the fact which helps in improvement of MobiL's energy-efficiency. Apart from these, MobiL does not require Received Signal Strength Intensity (RSSI) estimation. Therefore, the range estimation is free from multipath and fading effects.

The rest of the paper is organized as follows. We briefly present the related literature in Section II, and introduce the proposed localization scheme in Section III. We evaluate the simulation results in Section IV, and discuss the performance of the proposed scheme. Lastly, we conclude the paper while citing few research directions in Section V.

978-1-4673-5952-8/13/$31.00

II. Related Works

In the last few years, lot of research work on localization in UWSNs emerged [1], [2]. In the early works [6], localization was studied mainly for small-scale stationary networks, and these schemes exhibit performance challenges such as high communication overhead and low convergence rate. Some of the existing works such as [7] and [8] transform the 3D localization problem into the 2D version of its by using the depth information and projection technique. However, these are only limited to stationary UWSNs, and the schemes use 'active' messaging for localization. Localization Scheme for Large Scale underwater networks (LSLS) [9] and another localization scheme [10] was proposed for stationary UWSNs.

One of the existing localization schemes, named Dive'N'Rise localization (DNRL) [11], was proposed specifically for MUSNs. In this scheme, the Dive'N'Rise (DNR) mobile beacons dive and rise through the ocean column, and announce their location. Initially, the DNR beacons receive their coordinates using GPS while they float above the water surface. The underwater nodes 'silently' localize themselves by listening to several beacons. However, the requirement of large number of DNR beacons for large-scale networks is one of the disadvantages of this scheme. Another disadvantage of this method is that, node mobility greatly affects the localization performance due to the slow speed of the beacons.

In Ref. [12], a 3D localization scheme, named Three Dimensional Localization Algorithm for Underwater Acoustic Sensor Networks (3DUL), was proposed. In this scheme, an anchor node declares its presence by broadcasting a 'anchor ranging' message. The sensor nodes request for the locations of anchor nodes by sending 'ranging' packet, and get the coordinates of the anchors from the reply message. The distance between the unlocalized and the anchor node is estimated using two-way Time-of-Arrival (ToA). Although, 3DUL does not require time-synchronization between the nodes, the localization time required is very high. Mirza *et al.* proposed a localization scheme for MUSNs based on propagation delay and node mobility factors. It accounts for the location estimation error due to non-coherent distance measurement [13]. However, this method is criticized for its intense computation and lack of time-synchronization issues. In Scalable Localization with Mobility Prediction (SLMP) [14], the anchor nodes predict their future locations using their previous locations and their mobility patterns. Also, the anchor nodes estimate their locations using the lateration technique, with receiving coordinates from the surface buoys. The mobility pattern is assumed to be valid if the difference between the predicted and the estimated location is less than a threshold value. The ordinary nodes update their mobility pattern and locations by receiving coordinates from the anchors. Due to the exploitation of the underwater mobility patterns, SLMP results in low protocol overhead. However, the assumption of such anchor nodes which can directly communicate with the surface buoys is infeasible.

Few AUV based localization schemes for UWSN were proposed in [15], [16], [17]. These schemes use an AUV as the location beacon provider to the underwater nodes. However, these schemes introduce additional implementation cost [17], some of these methods introduce high localization delay (such as [15] and [16]), and some consider sensor nodes to be stationary (such as [16]).

III. Description of MobiL

A. Assumptions

For the design of our localization protocol, we assumed 3-dimensional deployment of underwater sensor nodes in a large area. All the sensor nodes are homogeneous, i.e., they are of the same type and are able to calculate their depth by the onboard pressure sensor with them. These sensor nodes are affected by passive node mobility, which is different at different horizontal layers of the water. We also assume that three anchor nodes, empowered with GPS facility, are deployed at the water surface. However, the sensor nodes are time-synchronized with one another.

B. Design Philosophy

Our design philosophy is to provide a *simple*, *accurate*, yet *energy-efficient* localization service to the underwater sensor nodes. Taking inspiration from SLMP [14], we exploit the spatially correlated mobility patterns of underwater sensor nodes to predict their node mobility. We characterize the distinct features of our proposed scheme as follows :

a. *No super node/special powered anchor node is required.*
b. *The location estimation is accurate in MUSNs.*
c. *The scheme is simple and requires low implementation cost.*
d. *Free from the estimation of RSSI.*
e. *Silent and time-synchronization based.*

C. Procedure

The localization process in MobiL is divided into two phases. During the first phase, *Mobility Prediction*, each node predicts its mobility pattern by exploiting the mobility patterns of the neighbour nodes. The sensor nodes localize themselves by listening to atleast three beacon messages from the anchors in the second phase, *Ranging and Localization*.

1) Mobility Prediction: All the sensor nodes are affected by underwater currents acting along the horizontal ocean layer. Therefore, the underwater current velocity depends on the depth of the layer, i.e., for any node j located at d depth, then $\vec{v_j} = ({v_j}^x(d), {v_j}^y(d), 0)$. Here, ${v_j}^x(d)$ and ${v_j}^y(d)$ are the components of the underwater current along x-axis and y-axis, respectively. To simplify the scenario, we neglect the component of node mobility along z-axis.

The spatially correlated motion of underwater sensor nodes show a group-like behavior, where the passive node mobility/velocity of a node can be estimated from the velocities of its neighbours. We can estimate the velocity of a node along the x- and y-axes as follows [18], [19]:

$$v_j{}^x(d) = \sum_{i=1}^{n} \zeta_{ij} v_i{}^x(d) \qquad v_j{}^y(d) = \sum_{i=1}^{n} \zeta_{ij} v_i{}^y(d) \tag{1}$$

Here, n is the number of neighbours of the node j and ζ_{ij} is the interpolation coefficient; $\zeta_{ij} = \frac{\frac{1}{r_{ij}}}{\sum_{i=1}^{n} \frac{1}{r_{ij}}}$, where, r_{ij} is the euclidean distance between nodes i and j.

In this phase of the algorithm, all the sensor nodes exchange periodic messages, named *velocity beacons*, between themselves, for $T_{MobilityPrediction}$ time. This beacons contain the speed vector ($\vec{v_j}$) of the corresponding node (j). Increasing the beacon sending interval (t_{vb}) results in less number of beacons, and decreasing this parameter leads to more frequent beacon sending.

2) Ranging and Localization: In this phase, a sensor node localizes itself by 'silently' listening to three *location beacons* from atleast three different anchor nodes. Let us assume that any unlocalized node S receives three beacon messages at time instants t_1, t_2, and t_3 from three anchors A_1, A_2, and A_3, respectively. We assume that the locations of S are (x,y,z), (x',y',z'), and (x'',y'',z'') at time t_1, t_2, and t_3, respectively. The scenario is explained in Figure 1. For each beacon message received, the inter-node-distance (d_i) is calculated as, $d_i = (t_A - t_S) \times V$, where, t_A and t_S are the time instants when the beacon message was sent from the anchor and received at the sensor node, respectively. Here, V is the velocity of sound.

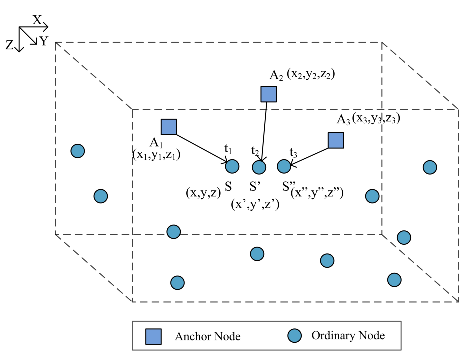


Fig. 1: The Proposed Localization Scenario

According to Figure 1,

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = d_1{}^2 \tag{2}$$

$$(x' - x_2)^2 + (y' - y_2)^2 + (z' - z_2)^2 = d_2{}^2 \tag{3}$$

$$(x'' - x_3)^2 + (y'' - y_3)^2 + (z'' - z_3)^2 = d_3{}^2 \tag{4}$$

Using Equation 1, we can calculate,

$$x' = x + (t_2 - t_1) \times v_j{}^x \tag{5}$$

$$y' = y + (t_2 - t_1) \times v_j{}^y \tag{6}$$

Similarly, x'' and y'' can be calculated. Also, $z = z' = z''$, and it is calculated using the onboard pressure sensor. Therefore, the term $(z - z_i)$ is constant ($i = 1, 2, 3$). Replacing these values in Equations 2, 3, and 4, a node can successfully determine its location, and acts as a anchor node for the unlocalized nodes.

Algorithm 1: MobiL procedure

Mobility Prediction:
while $t <= T_{MobilityPrediction}$ **do**
  Broadcast *Velocity beacon*;
  Update v using Equation 1;
  $t = t + t_{vb}$;
Ranging & Localization:
if *Number of received* location beacon >= *3* **then**
  Calculate x, y using Equations 2, 3, 4, 5, 6;
  Calculate z using the onboard pressure sensor;

IV. Performance Evaluation

A. Simulation Settings

We evaluated the performance of the proposed protocol by simulations in NS-3 (http://www.nsnam.org/). The simulation settings are described in Table I.

TABLE I: Simulation Parameters

Parameter	**Value**
Number of nodes	Varied between 50-200
Simulation area	150 m × 150 m × 150 m
Transmission range	100 m
Mobility model	Meandering current mobility model [20]
Node mobility	Varied between 1-5 m/s
Simulation time	Mobility prediction - 100 s Ranging and localization - 80 s
No. of prediction message	10
Transmission frequency	22 KHz

B. Performance Metrics and Benchmark

The performance of the proposed scheme was evaluated using the following metrics:

- *Localization Error:* It is measured as the Euclidean distance between the sensor node's estimated location (x,y,z) and the original location (x',y',z'). Therefore, localization error $\epsilon = \sum_{i=1}^{N} \sqrt{(x_i - x_i')^2 + (y_i - y_i')^2 + (z_i - z_i')^2}$
- *Localization Coverage:* Localization coverage is defined as the ratio of localized nodes to the total number of nodes. A node is considered to be localized, if the localization error (ϵ) is less than the error threshold (γ).
- *Communication Overhead:* It is the ratio of the number of messages per localized node. Energy consumption of a node is directly proportional to the communication overhead.

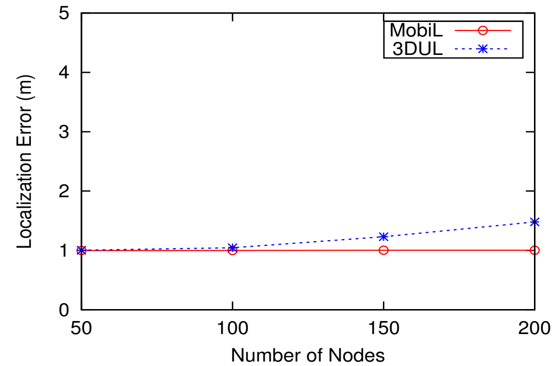
For comparing the performance of the proposed scheme, we used 3DUL [12] as the benchmark. This scheme also exploit localization in a distributed and iterative manner. Here, localization starts at the anchor nodes, and gradually iterates in all directions. In 3DUL, the inter-node distance is estimated using two-way message transfer. This scheme uses ‘active’ messaging.

C. Results and Discussions

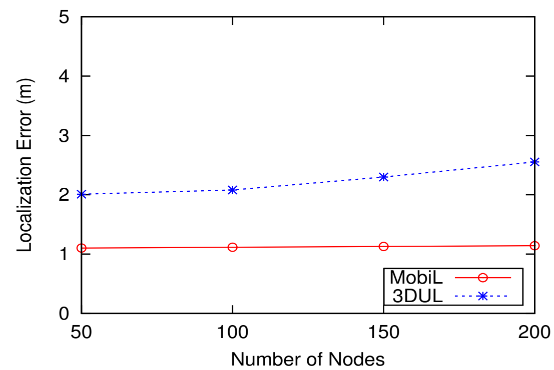
1) Effect of Node Mobility: In Figure 2, we plot the localization error for different scenarios varying the number of nodes. The error threshold (γ) value was set to 5 m. The node mobility was set to 1.0, 2.0, and 5.0 m/s and the localization error was measured for both MobiL and 3DUL. The results show that the localization error in MobiL is less than that of 3DUL, and the localization error in MobiL increases slightly with increase in node mobility. In 3DUL, an increase in node mobility results in higher error in location estimation as explained in Section III-C1. Due to the use of mobility prediction technique, MobiL is capable of estimating the location of a sensor node with less error. However, due to the noise in distance measurement and noise in velocity prediction, the localization error arises. The localization error varies between 25-30% of the error threshold.

2) Localization Coverage: The results for localization coverage is shown in Figure 3. It is shown that with the increase in the total number of nodes present in the simulation area, more number of nodes get localized successfully. However, the number of localized nodes is more in MobiL than 3DUL. This is due to the fact that MobiL requires simple and less number of beacon message exchange, and also, these messages are received ‘silently’. Moreover, the estimation of node mobility empowers the proposed scheme to successfully localize more number of nodes in less time.

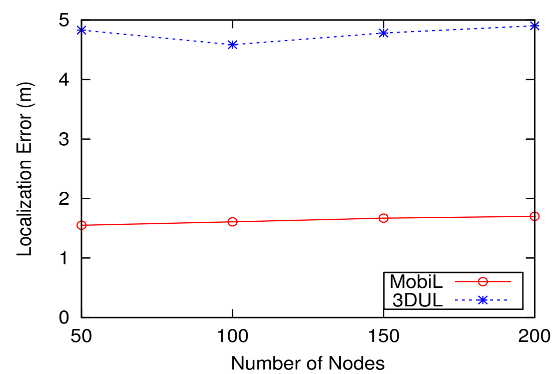
3) Average Communication Cost: The average number of beacon messages per localized node is plotted in Figure 4. Here, we consider the beacon messages for the *ranging and localization* phase as well as the *mobility prediction* phase also. The results show that with increase in the node density (i.e., number of nodes in the deployment area), the average number of beacon message required for localizing a sensor node decreases. Also, with increase in the passive node mobility, nodes require more number of beacons for successful localization, on an average. Therefore, the average communication cost incurred in MobiL is low due to the requirement of small number of beacon messages and ‘silent’ messaging.



(a) Node Mobility = 1.0 m/s



(b) Node Mobility = 2.0 m/s



(c) Node Mobility = 5.0 m/s

Fig. 2: The effect of node mobility on localization error

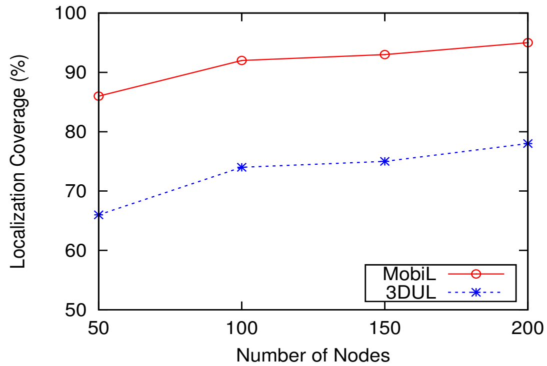
V. Conclusion

In this paper, we proposed a distribute and efficient scheme for localization in MUSNs. The localization procedure initiates from the three anchors located at water surface. The underwater sensor nodes passively listen to the beacons from anchors. First, the neighbours of these anchors are localized and iteratively localization spreads among the rest of the nodes. The sensor nodes are able to predict their mobility and incorporate this in estimating their locations. We analyzed the effect of passive node mobility on localization error. The simulation results show that MobiL results in accurate location estimation. Also, the location estimation is fast and energy-efficient due to the passive listening of beacon messages. We also analyzed the effect of variable sound speed on the performance of our protocol.

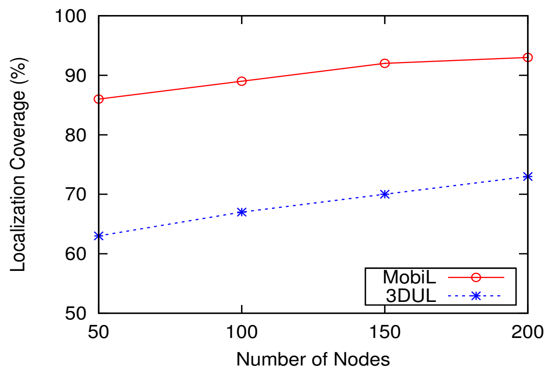
We plan to extend our future works on two directions: 1) testing of our protocol under various underwater scenario such as jamming [21] and variable sound speed [22], and shadow zone, 2) evaluating the effect of various upper layer protocol on the proposed scheme.

References

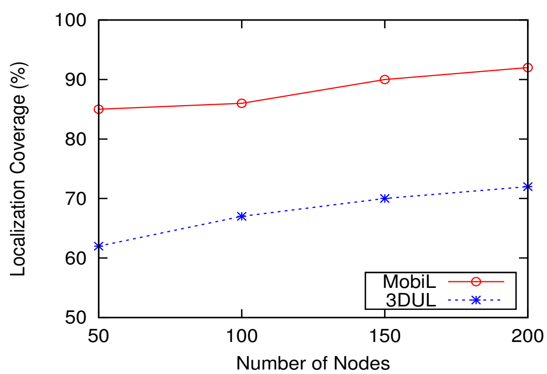
[1] M. Erol-Kantarci, H. T. Mouftah, and S. Oktug, “A survey of architectures and localization techniques for underwater acoustic sensor



(a) Node Mobility = 1.0 m/s



(b) Node Mobility = 2.0 m/s



(c) Node Mobility = 5.0 m/s

Fig. 3: The effect of node mobility on localization coverage

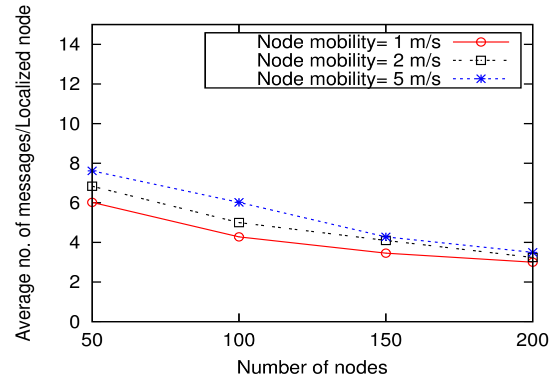


Fig. 4: Average number of beacon messages per node

networks," *IEEE Communications Surveys and Tutorials*, vol. 13, no. 3, pp. 487–502, 2011.

[2] H.-P. Tan, R. Diamant, W. K. G. Seah, and M. Waldmeyer, "A survey of techniques and challenges in underwater localization," *Ocean Engineering*, vol. 38, pp. 1663–1676, 2011.

[3] P. Xie, J.-H. Cui, and L. Lao, "VBF: vector-based forwarding protocol for underwater sensor networks," in *Proceedings of IFIP Networking*, 2006, pp. 1216–1221.

[4] J.-H. Cui, J. Kong, M. Gerla, and S. Zhou, "Challenges: Building scalable mobile underwater wireless sensor networks for aquatic applications," *IEEE Network*, vol. 20, no. 3, pp. 12–18, 2006.

[5] I. F. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: Research challenges," *Ad Hoc Networks*, vol. 2, no. 3, pp. 257–279, 2005.

[6] J. E. Garcia, "Ad hoc positioning for sensors in underwater acoustic networks," in *Proceedings of MTS/IEEE Oceans*, 2004, pp. 2338–2340.

[7] W. Cheng, A. Y. Teymorian, L. Ma, X. Cheng, X. Lu, and Z. Lu, "Underwater localization in sparse 3d acoustic sensor networks," in *Proceedings of IEEE INFOCOM*, 2008, pp. 236–240.

[8] A. Y. Teymorian, W. Cheng, L. Ma, X. Cheng, X. Lu, and Z. Lu, "3D underwater sensor network localization," *IEEE Transactions on Mobile Computing*, vol. 8, no. 12, pp. 1610–1621, 2009.

[9] W. Cheng, A. Thaeler, X. Cheng, F. Liu, X. Lu, and Z. Lu, "Time-synchronization free localization in large scale underwater acoustic sensor networks," in *Proceedings of International Conference on Distributed Computing Systems(ICDCS) Workshop*, 2009, pp. 80–87.

[10] X. Cheng, H. Shu, Q. Liang, and D. H.-C. Du, "Silent positioning in underwater acoustic sensor networks," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 3, pp. 1756–1766, 2008.

[11] M. Erol, L. F. M. Vieira, and M. Gerla, "Localization with DiveNRise (DNR) beacons for underwater acoustic sensor networks," in *Proceedings of ACM WUWNet*, 2007, pp. 97–100.

[12] M. T. Isik and O. B. Akan, "A three dimensional localization algorithm for underwater acoustic sensor networks," *IEEE Transactions on Wireless Communications*, vol. 8, no. 9, pp. 4457–4463, 2009.

[13] D. Mirza and C. Schurgers, "Motion-aware self-localization for underwater networks," in *Proceedings of ACM WUWNet*, 2008, pp. 51–58.

[14] Z. Zhou, Z. Peng, J.-H. Cui, Z. Shi, and A. C. Bagtzoglou, "Scalable localization with mobility prediction for underwater sensor networks," *IEEE Transaction on Mobile Computing*, vol. 10, no. 3, pp. 335–348, 2011.

[15] M. Erol, L. F. M. Vieira, and M. Gerla, "AUV-aided localization for underwater sensor networks," in *Proceedings of Wireless Algorithms, Systems and Applications*, 2007, pp. 44–54.

[16] M. Waldmeyer, H.-P. Tan, and W. K. G. Seah, "Multi-stage AUV-aided localization for underwater wireless sensor networks," in *Proceedings of Advanced Information Networking and Applications*, 2011, pp. 908–913.

[17] T. Ojha and S. Misra, "HASL: High-speed AUV-based silent localization for underwater sensor networks," in *Proceedings of the 9^{th} International Conference on Heterogeneous Networking for Quality, Reliability, Security and Robustness*. Greater Noida, India,: Springer, 2013.

[18] A. Novikov and A. Bagtzoglou, "Hydrodynamic model of the lower hudson river estuarine system and its application for water quality management," *Water Resources Management*, vol. 20, no. 2, pp. 257–276, 2006.

[19] A. Bagtzoglou and A. Novikov, "Chaotic behavior and pollution dispersion characteristics in engineered tidal embayments: A numerical investigation," *Journal of American Water Resources Association*, vol. 43, no. 1, pp. 207–219, 2007.

[20] A. Caruso, F. Paparella, L. F. M. Vieira, M. Erol, and M. Gerla, "The meandering current mobility model and its impact on underwater mobile sensor networks," in *Proceedings of IEEE INFOCOM*, 2008, pp. 221–225.

[21] S. Misra, S. Dash, M. Khatua, A. Vasilakos, and M. Obaidat, "Jamming in underwater sensor networks: Detection and mitigation," *IET Communication*, vol. 6, no. 14, pp. 2178–2188, 2012.

[22] S. Misra and A. A. Ghosh, "The effects of variable sound speed on localization in underwater sensor networks," in *Proceedings of Australasian Telecommunication Networks and Applications Conference*, 2011, pp. 1–4.