An Enhanced Underwater Positioning System to Support Deepwater Installations

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***Abstract*—In the offshore engineering community, deep underwater construction activities such as installation of mooring systems for oil and gas extraction require payloads such as subsea templates, christmas trees and manifolds to be installed accurately. In this paper, we consider a recently proposed underwater positioning system (UPS) to support deepwater installations. We identify and demonstrate its shortcomings in harsh underwater acoustic channels. We then propose enhancements to UPS, and demonstrate numerically that our proposed scheme achieves significantly better localization speed, at lower communication costs while preserving the "silent" property with a relatively small underwater acoustic sensor network deployed on the seabed in typically underwater channel conditions.**

I. INTRODUCTION

In the offshore engineering community, deep underwater construction activities such as installation of mooring systems for oil and gas extraction require subsea templates, christmas trees and manifolds to be installed accurately, e.g., within 25 cm of design location. These payloads are lowered from the bridge of an installation vessel, and their positioning can be actively controlled via "intelligent crane hooks" or ROV operators tethered to the installation vessel. For localization, we assume that an underwater acoustic sensor network (UASN) is deployed on the seabed at known positions[1], and each payload to be installed is fitted with an acoustic transducer as well as a pressure sensor [1]. As the payload approaches the seabed, it is localized at incremental depths, and its position is relayed via acoustic transducers fitted along the installation cable. The position offset is then corrected through the crane hooks, ROV or by maneuvering the installation vessel. Due to the high daily costs of the crane barge and the marine spread for the installation operation, payload positioning should be performed in a *timely* and *reliable* manner during the brief weather windows in which installations could be safely performed. Once the payloads are installed, their positions will be continuously monitored via the UASN as the mooring system is subject to weather conditions such as wind and hurricanes, which may cause the system to be dislodged.

Since the UASN and the payloads will be installed in deep waters for long periods of time (e.g., for oil and gas extractions), it is also desirable that the localization scheme will be energy-efficient and require no time synchronization. Underwater Positioning System (UPS) [2] is a suitable underwater localization scheme since it (i) requires no time synchronization, (ii) provides silent positioning, (iii) has low computation overhead and (iv) has been shown to exhibit low positioning error. In this study, we identify the limitations in UPS and propose enhanced UPS (E-UPS), and evaluate its efficacy for positioning in deepwater installations numerically.

The paper is organized as follows: we describe related work in this area and define our system model in Section II and III respectively. Next, we describe UPS, evaluate its performance and identify its limitations in Section IV. Following this, we propose an enhanced-UPS (E-UPS) and describe its design in Section V. We evaluate the performance of E-UPS against UPS numerically in Section VI. Finally, we provide some concluding remarks and directions for future research in Section VII.

II. RELATED WORK

Since GPS signals do not propagate through water, underwater nodes need to rely on position references for localization, obtained either through spatial (multiple, fixed references) or time diversity (single, mobile reference). Accordingly, in the survey in [1], underwater localization techniques have been classified as infrastructure-based vs infrastructure-less respectively. Taking into account the network architecture, underwater localization techniques proposed since then can be further categorized as single-stage [2]–[5] vs hierarchical / multi-stage [6]–[8].

In infrastructure-based localization, reference nodes are deployed on surface buoys (localized using GPS) or at predetermined locations on the seabed. Based on the beaconing signals from the reference nodes, the distance to these reference nodes can be computed at the payload to be localized using the propagation time. In general, there should exist at least $d + 1$ references to uniquely localize a payload in d-dimensional space. Underwater Positioning System (UPS) [2] is a single-stage localization scheme that exhibits many desirable properties (see Section I), it assumes that the reference nodes cover the entire network, and thus limits the area of interest. This drawback can be overcome with multi-stage [6] and hierarchical localization [7], [8]. In [6], the authors propose a purely distributed localization framework that employs a projection technique that transforms the 3D underwater positioning problem into its 2D counterpart. In

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[1] Such an UASN may be deployed to serve a multitude of applications, including seabed monitoring for seismic activities as well as marine life monitoring.

0-933957-38-1/09/$20.00

[7], the authors divide the localization process into two subprocesses: anchor node localization and ordinary node localization. They propose a distributed localization scheme that integrates 3D Euclidean distance estimation with a recursive location estimation method. This method is enhanced in [8] by introducing mobility prediction based on the predictable mobility patterns of underwater objects.

Infrastructure-less localization is usually implemented by using mobile beacon(s). In [9], the authors proposed Dive-and-rise beacons that get their coordinates from GPS while floating above water, and then dive into water. While sinking and rising, they broadcast their positions. The multi-stage extension of this approach for large-scale networks is given in [9]. The need for synchronization amongst nodes with the above approaches is eradicated with AUV-aided localization using omnidirectional [4] or directional antennae [5].

III. SYSTEM MODEL

We assume that there is a UASN comprising N nodes on the seabed, with a coverage of $X \times Y$, where each node knows its own coordinates. This is illustrated in Fig. 1. Let the payload to be installed be denoted by S, with location (x_S,y_S,z_S) such that z_S is determined by a pressure sensor. Without loss of generality, we assume that S falls within the coverage of the UASN when projected onto the seabed.

Localization of node S takes place when it has reached a certain depth (near the seabed). At this instant, node S will send a short beacon to wake up the UASN. All UASN nodes that hear this beacon (i.e., that are within communication range of, and maintains a good communication link with, S) will respond with their ID, coordinates, the arrival time of S's wake-up beacon and the transmission time of the response beacon. Let R denote this set of UASN nodes. We assume that each beaconing signal comprises a fixed-size packet, and the probability of packet transmission failure is p.

In our application scenario, the payload as well as the UASN will be deployed for the entire duration of the mooring operation. Hence, in addition to positioning accuracy, it is desirable to minimize the number of transmissions needed by the payload ("silent" property) as well as the UASN for the localization process. In addition, since installations can only be safely performed during brief weather windows, the time required for localization should also be minimized.

Let T be the time required for successful localization, with respect to t_0, and let n_s and n_{total} be the total number of transmissions (from time t_0) by node S and all nodes respectively until S is successfully localized.

IV. UNDERWATER POSITIONING SYSTEM (UPS)

In this section, we describe the UPS algorithm, and identify its limitations. Then, we will analyse its performance in terms of localization latency and energy consumption, where the latter is quantified in terms of the expected number of transmissions until successful localization. In addition, we will quantify the "silent" property in terms of the total number of transmissions from node S (excluding the wake-up beacon) until successful localization.

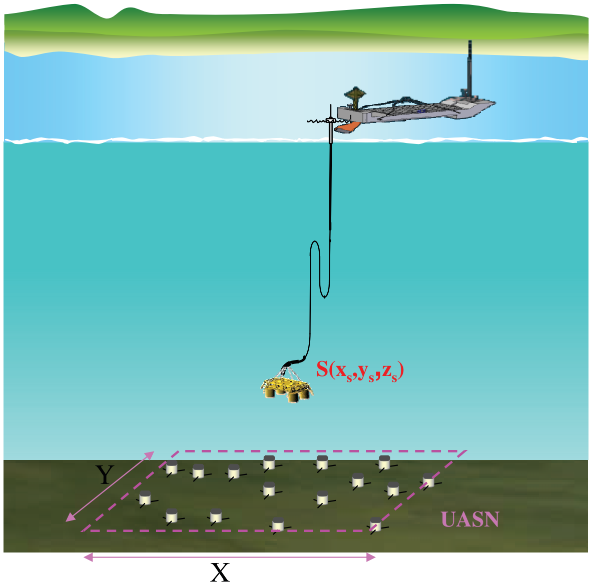


Fig. 1. Localization Scenario.

A. Algorithm Description

The UPS algorithm is illustrated in Fig. 2. At time t_0, node S will select and notify 3 nodes (denoted by 1,2 and 3 for simplicity) within set R as reference nodes. Let their locations be (x_1, y_1, z_1), (x_2, y_2, z_2) and (x_3, y_3, z_3) respectively. When node 1 (master node) receives the notification from S at t^S_1, it initiates a beacon signal, which is received at node 2, 3 and S at $t^R_{2,1}$, $t^R_{3,1}$ and $t^R_{S,1}$ respectively. At some time $t^S_2 = t^R_{2,1} + \delta_2$ (where δ_2 is the processing delay at node 2), node 2 *responds* to node 1's beacon by transmitting $\Delta t_{2,1}$ = t^S_2 - $t^R_{2,1}$, and this signal reaches node 3 and S at $t^R_{3,2}$ and $t^R_{S,2}$ respectively. Similarly, at $t^S_3 = t^R_{3,2} + \delta_3$, upon receiving beacons from both nodes 1 and 2, node 3 transmits $\Delta t_{3,1}$ = t^S_3 - $t^R_{3,1}$, and this signal reaches node S at $t^R_{S,3}$. This is illustrated in Fig. 2(a).

Writing $\Delta t^S_{2,1}$ = $t^R_{S,2}$ - $t^R_{S,1}$ and $\Delta\ t^S_{3,1}$ = $t^R_{S,3}$ - $t^R_{S,1}$, we can solve for (x_S,y_S) and d_{S1} using the following set of equations:

$$\begin{aligned}
(x_S - x_1)^2 + (y_S - y_1)^2 + (z_S - z_1)^2 &= d_{S1} \\
(x_S - x_2)^2 + (y_S - y_2)^2 + (z_S - z_2)^2 &= (d_{S1} + k_1)^2 \\
(x_S - x_3)^2 + (y_S - y_3)^2 + (z_S - z_3)^2 &= (d_{S1} + k_2)^2,
\end{aligned}$$

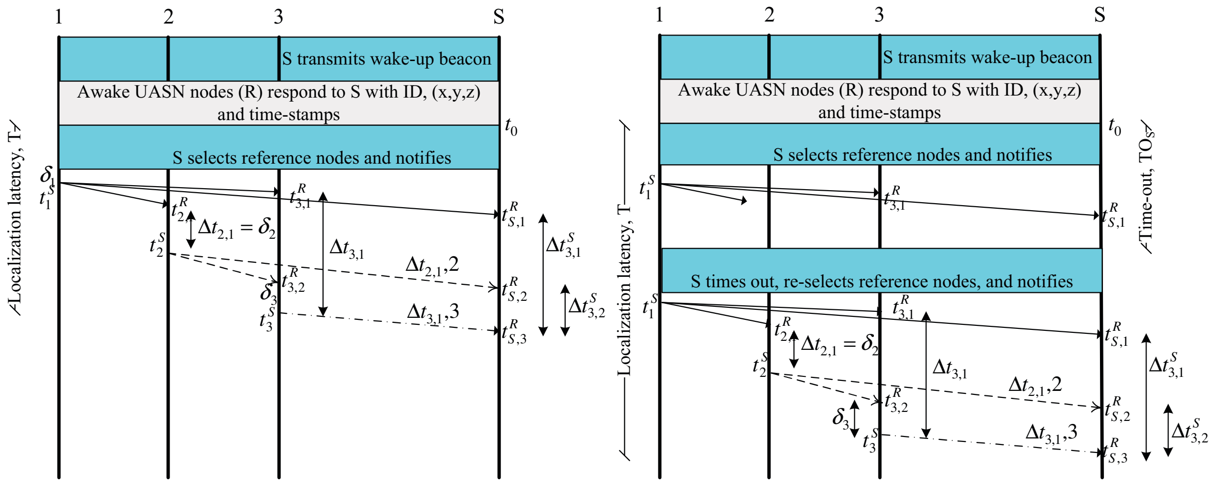
where

$$\begin{aligned}
k_1 &= c\Delta t^S_{2,1} - d_{12} - c\Delta t_{2,1} \\
k_2 &= c\Delta t^S_{3,1} - d_{13} - c\Delta t_{3,1}
\end{aligned}$$

, d_{ab} is the distance between nodes a and b, and c is the speed of sound underwater.

B. Limitations of UPS

Although UPS possesses various desirable properties, the current design suffers from several drawbacks as it does not take into account the impact of transmission failures, which is



(a)

(b)

Fig. 2. Illustration of Underwater Positioning System (UPS): successful localization (a) without, and (b) with time-out.

highly likely as underwater acoustic channels are unreliable. Specifically:

- **Reactive Beaconing**
  Upon receiving S's wake-up beacon, node 1 initiates the beaconing, to which the other reference nodes 2 and 3 respond to. Localization will be unsuccessful if (i) node 1 does not receive S's wake-up beacon, (ii) node 1's beacon does not reach node 2, (iii) node 2's beacon does not reach node 3.
- **Fixed reference nodes**
  The successful localization of node S is conditioned upon successful communication amongst a *fixed* set of nodes. In the event that a particular link is "down", UPS will fail, even if it is iterated several times.

If localization fails for reasons cited above, we let node S time-out after some time TO_S, in order to re-initiate the UPS algorithm described in Section IV-A, possibly by choosing a different set of reference nodes within R. For example, in Fig. 2(b), localization fails initially because node 2 fails to receive node 1's beacon, but is successful in the next attempt after S times out.

C. Design and Performance Analysis

Let t_p be the packet transmission time, and assume that $x_s \le X$ and $y_s \le Y$. In addition, the processing delays δ_2 and δ_3 can be computed at S based on the time-stamps it receives in response to the wake-up beacon.

Referring to Fig. 2(a), if all transmissions are successful, the localization time required with respect to t_0 is given by:

$$T_0 = \tau_{S,1} + \tau_{1,2} + \tau_{2,3} + \tau_{3,S} + \sum_{i=1}^{3} \delta_i + \delta_s + 4t_p,$$

where $\tau_{a,b}$ is the propagation delay incurred for sending a message from node a to node b. By projecting S onto the plane formed by the line joining nodes 1 and 3 and orthogonal to the x-y plane (denoted by S'), as shown in Fig. 3, and applying the triangular inequality, we obtain the following:

$$\tau_{1,S'} + \tau_{3,S'} \le \frac{z_S}{c} + \sqrt{(\frac{z_S}{c})^2 + \tau_{1,3}^2}.$$

Since $d_{1S} \le d_{1S'} + d_{SS'}$ and $d_{3S} \le d_{3S'} + d_{SS'}$, we have the following:

$$\tau_{1,S} + \tau_{3,S} \le \frac{z_S}{c} + \sqrt{(\frac{z_S}{c})^2 + \tau_{1,3}^2} + 2\tau_{SS'}.$$

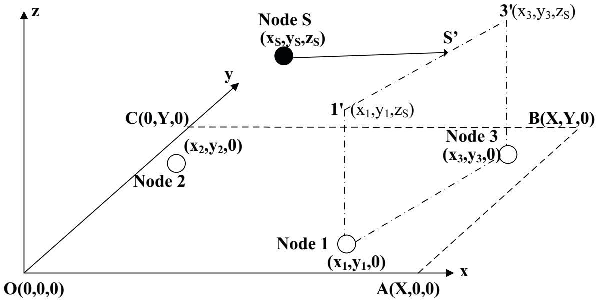


Fig. 3. Illustration of the computation of TO_S for UPS.

Since S' is constrained to lie on the line joining 1' and 3', we can write the following:

$$\tau_{SS'} \le \frac{\max\limits_{n=1:3}\{d_{nO},\ d_{nA},\ d_{nB},\ d_{nC}\}}{c} \equiv \tilde{\tau}_{13}.$$

Hence, we can express T_0 as follows:

$$\begin{aligned} T_0 &\le \tau_{1,2} + \tau_{2,3} + \frac{z_S}{c} + \sqrt{(\frac{z_S}{c})^2 + \tau_{1,3}^2} + 2\tilde{\tau}_{13} + \Delta \\ &\equiv T_{min}, \end{aligned}$$

where

$$\Delta = \sum_{i=1}^{3} \delta_i + \delta_s + 4t_p.$$

Hence, if S is unable to localize itself by T_{min}, it should trigger a time-out to re-initiate the localization procedure. Accordingly, we can set $TO_S = T_{min}$, i.e.,

$$TO_S = \tau_{1,2} + \tau_{2,3} + \frac{z_S}{c} + \sqrt{(\frac{z_S}{c})^2 + \tau_{1,3}^2} + 2\tilde{\tau}_{13} + \Delta.$$

Since node S knows the location of nodes 1,2 and 3, it will be able to compute TO_S at the time instant t_0.

Referring to Fig. 2(b), the *worst-case* localization latency is given by $T_{max} = TO_S + kTO_S$, where $k \geq 0$ is the number of time-outs until successful localization. For successful localization, the following message transmissions, $\{TX_{S,1}$, $TX_{1,2}$, $TX_{1,3}$, $TX_{1,S}$, $TX_{2,S}$, $TX_{2,3}$, $TX_{3,S}\}$, must all be successful, where $TX_{a,b}$ represents a transmission from node a to b. This occurs with probability, $\tilde{p} = (1-p)^7$.

Accordingly, we have:

$$P(T_{max} = TO_S + kTO_S) = \tilde{p}(1-\tilde{p})^k.$$

Hence, the expected worst-case localization time, E[T_{max}], is given by:

$$E[T_{max}] = \frac{TO_S}{\tilde{p}}.$$

Each round of localization attempt incurs a transmission from node S. Accordingly, we have:

$$P(n_s = k+1) = \tilde{p}(1-\tilde{p})^k.$$

As above, the expected number of transmissions from node S, E[n_s], is given by:

$$E[n_s] = \frac{1}{\tilde{p}}.$$

Within each round of localization attempt, the pmf of the total number of transmissions from the reference nodes, n, is given as follows:

$$\mathrm{P}(n = i) = \begin{cases} p, & i = 0; \\ (1-p)p, & i = 1; \\ (1-p)^2[p + (1-p)p], & i = 2; \\ (1-p)^4, & i = 3; \\ 0, & \text{otherwise.} \end{cases}$$

Accordingly, the expected number of transmissions from the reference nodes per round, E[n], can be evaluated as follows:

$$E[n] = (1-p)(3 - 4p + 3p^2 - p^3).$$

Therefore, the expected total number of transmissions till successful localization, E[n_{total}] is given as follows:

$$E[n_{total}] = \frac{1}{\tilde{p}}(E[n] + 1).$$

V. ENHANCED-UPS (E-UPS)

We propose the following modifications to address the limitations of UPS:

- **Dynamic Reference Nodes**
  To overcome the limitations of relying on the minimum number of (same) reference nodes, we extend the UPS scheme to *all* nodes in R. Specifically, node S will broadcast a beaconing sequence to be adopted by nodes in R, which is according to the order of arrival of the response beacons. As soon as S is successfully localized, it will broadcast a short message to terminate the beaconing; otherwise, it will trigger a time-out, as elaborated in Section V-B. When reference nodes receive the "terminate" message, they will stop transmissions.
- **Time-out Beaconing**
  Another drawback of UPS is that reference nodes j *respond* to beacons from node i, $j > i$; if node i's beacon is not received at node j, node j will not beacon, resulting in failure. To overcome this, along with the beaconing sequence, node S also broadcasts the beaconing time-out for each node i, TO_i, i.e., the *maximum* delay between receiving a beaconing sequence from S, and transmitting its own beacon, in the event that it fails to receive node i-1's beacon.
- **Measurement of $\Delta t_{k,j}$, $k > j$**
  Since node 1 is the designated master node in UPS, we only need to measure $\Delta t_{k,1}$, $k >$1. However, as there is no designated master node in E-UPS, we need to measure $\Delta t_{k,j}$, $k > j$, $j \geq 1$.

The Enhanced-UPS (E-UPS) algorithm is illustrated in Fig. 4.

Node S can be successfully localized as soon as it successfully receives node k's beacon, $\Delta t_{j,k}$, and $\Delta t_{m,k}$, where $k \in R$ and $m, j > k$. In the example illustrated in Fig. 4, where $\{1,2,3,4\} \in R$, node S can be successfully localized upon receiving node 2's beacon, $\Delta t_{3,2}$ and $\Delta t_{4,2}$ by solving the following equations:

$$\begin{aligned} (x_S - x_2)^2 + (y_S - y_2)^2 + (z_S - z_2)^2 &= d_{S2} \\ (x_S - x_3)^2 + (y_S - y_3)^2 + (z_S - z_3)^2 &= (d_{S2} + k_1)^2 \\ (x_S - x_4)^2 + (y_S - y_4)^2 + (z_S - z_4)^2 &= (d_{S2} + k_2)^2, \end{aligned}$$

where

$$\begin{aligned} k_1 &= c\Delta t_{3,2}^S - d_{23} - c\Delta t_{3,2} \\ k_2 &= c\Delta t_{4,2}^S - d_{24} - c\Delta t_{4,2}. \end{aligned}$$

While the UPS scheme is designed to be *collision-free*, there is a possibility that the "terminate" message from node S may collide with a beacon from a reference node. Here, we assume that upon detecting a collision, the reference node will terminate its transmissions.

A. Design of Reference Node Time-out (TO_i)

As stated earlier, the beaconing sequence is determined according to the order of arrival of the response to the wake-up beacon, i.e., we have the following condition:

$$\tau_{S,i} \leq \tau_{S,j}, \; i < j.$$

Let us consider nodes 1,2 and S. As illustrated in Fig. 5(a), the transmission $TX_{2,S}^1$ in response to node 2 receiving node 1's beacon should occur before $TX_{2,S}$, which is node 2's transmission if it fails to receive node 1's beacon. Accordingly, we have the following condition:

$$\tau_{S,2} + TO_2 + t_p + \delta_2 \geq \tau_{S,1} + \tau_{1,2} + \delta_1 + \delta_2 + 2t_p,$$

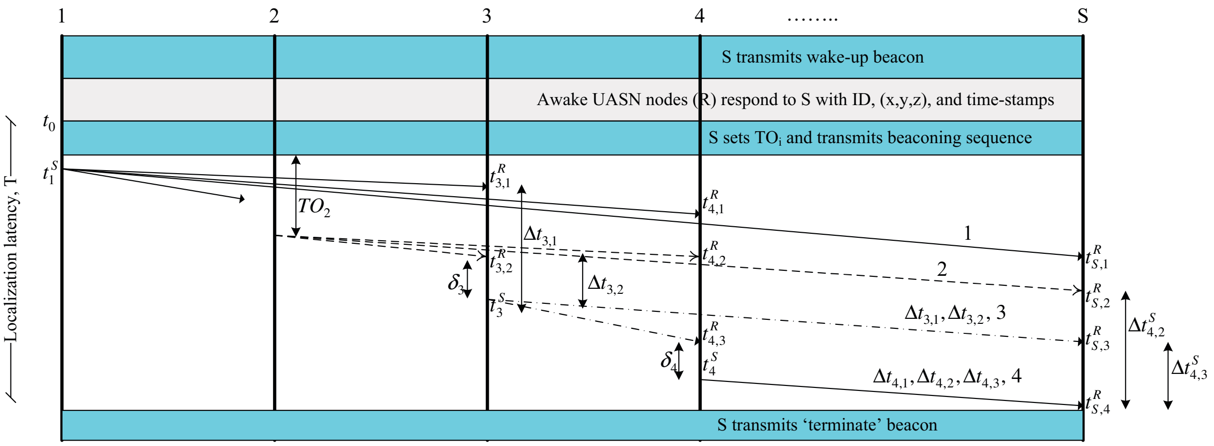


Fig. 4. Illustration of Enhanced-Underwater Positioning System (E-UPS).

i.e.,

$$TO_2 \geq \tau_{1,2} + \delta_1 + t_p - (\tau_{S,2} - \tau_{S,1}).$$

Since $\tau_{S,2} \geq \tau_{S,1}$, we can set TO_2 as follows:

$$TO_2 = \tau_{1,2} + \delta_1 + t_p.$$

Next, let us consider reference nodes, $\{i\text{-}1,\ i,\ i\text{+}1\}$ in beaconing sequence. In the worst-case scenario as illustrated in Fig 5(b), the transmission $TX^i_{i+1,S}$ in response to node i+1 receiving node i's beacon should occur before $TX_{i+1,S}$, which is node i+1's transmission if it fails to receive node i's beacon. Accordingly, we have the following condition:

$$\tau_{S,i+1} + TO_{i+1} + \delta_{i+1} + t_p \geq \tau_{S,i} + TO_i + \tau_{i,i+1} + \delta_i + \delta_{i+1} + 2t_p.$$

In a similar manner as above, since $\tau_{S,i+1} \geq \tau_{S,i}$, we can set TO_{i+1} in terms of TO_i as follows:

$$TO_{i+1} = TO_i + \tau_{i,i+1} + \delta_i + t_p.$$

Therefore, by induction, we can express TO_i, $i \geq 2$, $i \in R$, as follows:

$$TO_i = \sum_{j=1}^{i-1} [\tau_{j,j+1} + \delta_j] + (i-1)t_p.$$

B. Design of Time-out for Node S (TO_S)

With the time-out functionality at node S, UPS guarantees successful localization as long as $N \geq 3$ and there is no upper bound on the localization latency or energy consumption. Similarly, to guarantee successful localization with E-UPS, S can be triggered after TO_S to re-initiate the localization procedure.

In the worst-case scenario, node S needs to wait until it receives the beacon from reference node $|R|$ before it can be localized. The localization time, T', required is given by:

$$T' = TO_{|R|} + 2t_p + \delta_{|R|} + \delta_s + 2\tau_{|R|,S},$$

where $TO_{|R|}$ is the time-out of the last node in the beaconing sequence.

Since node S does not know its own location at t_0, referring to Fig. 3, we can write the following:

$$\tau_{|R|,S} \leq \frac{\sqrt{\tilde{d}^2 + z_S^2}}{c},$$

where $\tilde{d}$ = max $\{d_{|R|,O}, d_{|R|,A}, d_{|R|,B}, d_{|R|,C}\}$.

Since $TO_S \geq T'$, we can set TO_S as follows:

$$TO_S = TO_{|R|} + 2\frac{\sqrt{\tilde{d}^2 + z_S^2}}{c} + 2t_p + \delta_{|R|} + \delta_s.$$

VI. NUMERICAL RESULTS

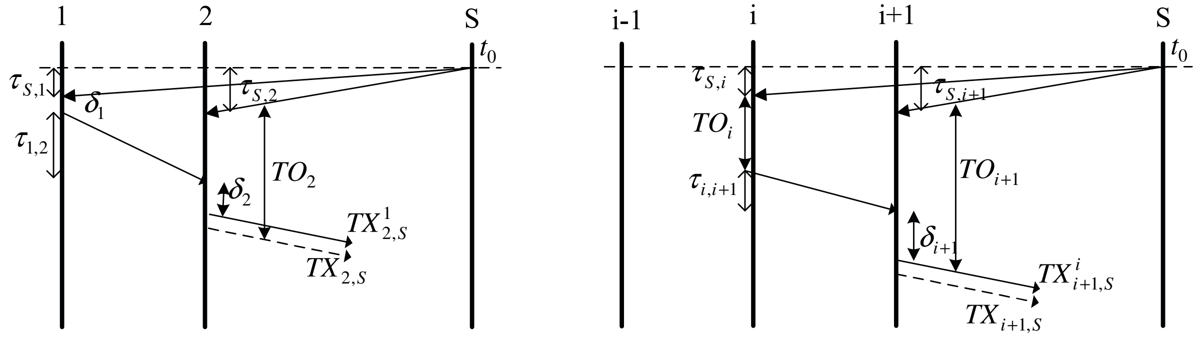
In this section, we compare the performance of UPS and E-UPS in terms of the localization speed (quantified by T), communication costs (quantified by n_{total}), and silent property (quantified by n_s) via simulations conducted using the Qualnet simulator [10]. For each parameter setting, we obtain the mean and 95% confidence interval over 1000 simulation runs.

We assume that the UASN comprises N nodes deployed as a 2-D regular grid, where each node has a communication range of D, and X = Y = 1000 without loss of generality. Unless otherwise stated, D is chosen to ensure that the UASN as well as node S forms a fully-connected network, and (x_s, y_s, z_s) = ($\frac{X}{2}$, $\frac{X}{2}$, 50). The latter choice ensures that S can be uniquely localized [2]. In addition, we also assume that the processing delay at each node is fixed at δ=0.01. The other simulation parameters used are defined in Table I.

A. Performance of UPS

We plot the 95% confidence intervals for T, n_{total} and n_s for the UPS scheme obtained from simulations as a function of p in Fig. 6 for various network sizes. We also plotted the corresponding analytical results derived in Section IV-C.

As expected, the performance of UPS degrades exponentially as the channel condition worsens. In addition, the analytical results fall within the 95% confidence interval obtained with the simulation results, validating the correctness of our analysis.



(a) (b)

Fig. 5. Computation of time-out (TO_i): (a) i = 2; (b) i >2.

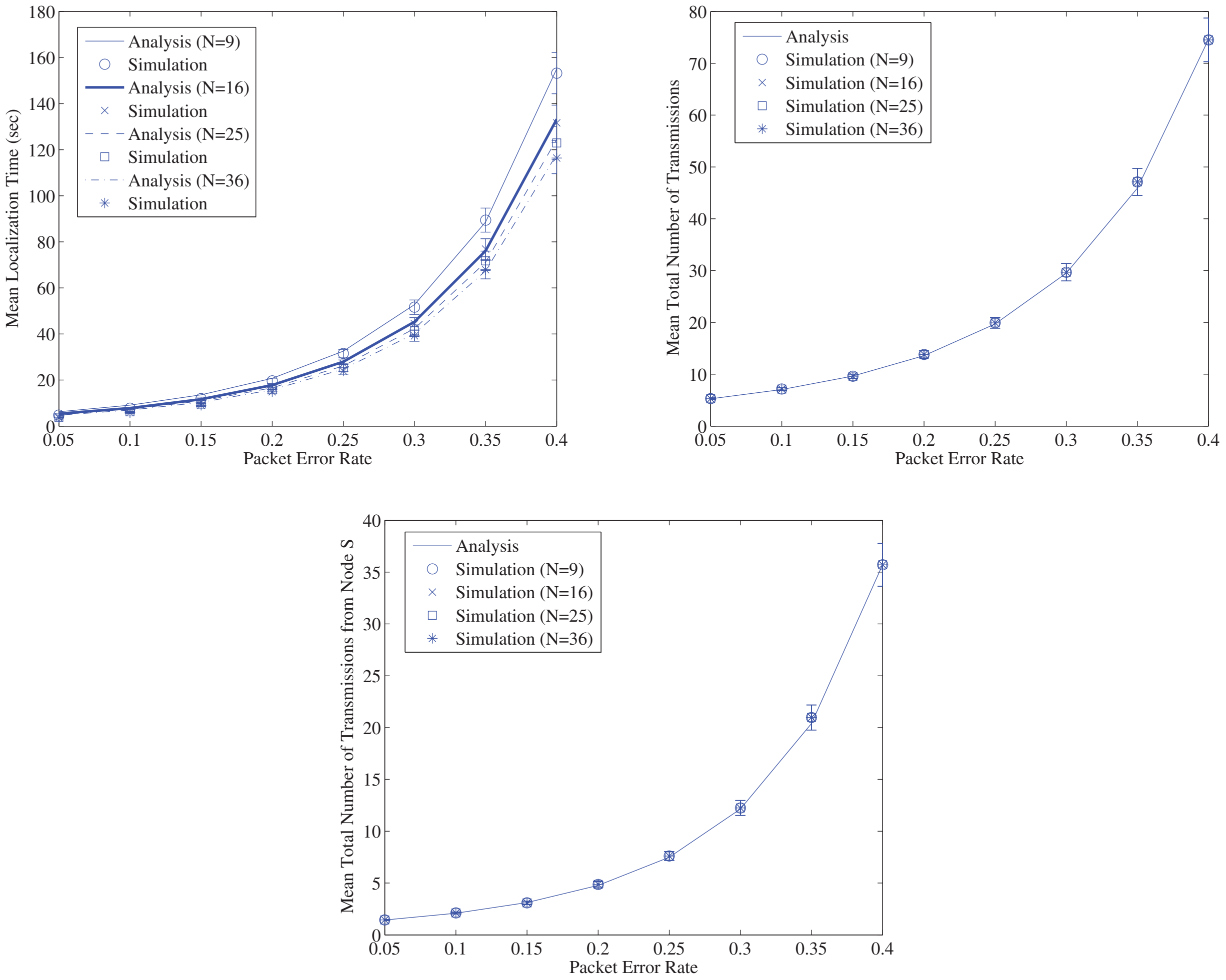


Fig. 6. Evaluation of localization latency and efficiency for UPS (X=1000, z_s = 50).

As network size (infrastructure costs) increases, the localization speed improves gradually since the reference nodes are spaced closer together, i.e., lower inter-node propagation delay. The total number of transmissions (communication costs) and transmissions from node S (silent property) remain invariant with packet error rate since the latter is independent of the link distance in our current channel model.

Simulation parameters	Value
p	[0.05-0.4]
N	[9, 16, 25, 36]
D^2 (m)	$2X^2+z_s^2$
data rate (kbps)	5
packet size (bytes)	256

TABLE I
SIMULATION PARAMETERS.

B. Performance of E-UPS

Next, we plot the 95% confidence intervals for T, n_{total} and n_s for the E-UPS scheme obtained from simulations as a function of p in Fig. 7 for various network sizes.

When the network is very small (N=9), the localization performance degrades exponentially as the channel condition worsens, as with the UPS scheme. As network size increases to 16, localization speed improves *significantly*. This is because the set of reference nodes is large enough such that the likelihood of node S timing-out is very low. As a result, node S only needs to transmit twice (the beaconing sequence and the "terminate" beacon), preserving the silent property of UPS even under poor channel conditions. Further increases in the network size only results in marginal improvements in localization speed.

The total number of transmissions increases exponentially with packet error rate for N=9 because transmissions from reference nodes are not terminated prior to S timing-out. However, with larger networks, localization completes without S timing-out. In fact, fewer redundant transmissions are terminated as N increases due to the near-far effect, giving rise to more transmissions.

Overall, the improvement in localization speed with larger networks is traded-off with increased total communication costs. Since the improvement in localization speed with N >16 is marginal, a 16-node UASN is sufficient to achieve overall good localization performance with E-UPS.

C. Summary: UPS vs E-UPS

We summarize by tabulating the percentage gain ($\{\frac{x_{UPS}-x_{E-UPS}}{x_{UPS}}\}_{x=E[T],E[n_{total}],E[n_s]}$) achieved by E-UPS over UPS in terms of localization speed, communication costs and "silent" property in Table II.

Under very good channel conditions (p = 0.05), the gain in localization speed with E-UPS over UPS is traded off with a degradation in the communication costs as well as "silent" property. However, as the channel is degraded (to typical levels experienced in underwater acoustic channels), E-UPS achieves a significant gain over UPS in all aspects of localization performance.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we consider the problem of localization for deepwater installations. We consider the recently proposed range-based Underwater Positioning System (UPS), which relies on minimal infrastructure and transmission from the node to be localized and more importantly, is not based on the premise of synchronized clocks. However, we demonstrate that the performance of UPS is poor and degrades significantly under harsh and dynamic channel conditions posed by an underwater acoustic environment.

To overcome these drawbacks, we propose various enhancements to UPS (denoted E-UPS), where we exploit the availability of an Underwater Acoustic Sensor Network deployed on the sea bed at known locations, to improve the robustness of localization in harsh underwater channel conditions. We show, via simulations, that E-UPS achieves better localization speed with lower communication costs than UPS, particularly under poor channel conditions, while preserving the "silent" property of UPS. In fact, a relatively small network (up to 16 nodes) is sufficient for E-UPS to achieve good overall localization performance under typical underwater channel conditions.

While our focus in this paper is on the impact of channel conditions on underwater localization, we plan to investigate the impact of network deployment on the feasibility region (i.e., for successful localization). In addition, we plan to consider a more realistic underwater acoustic channel model in future performance evaluations.

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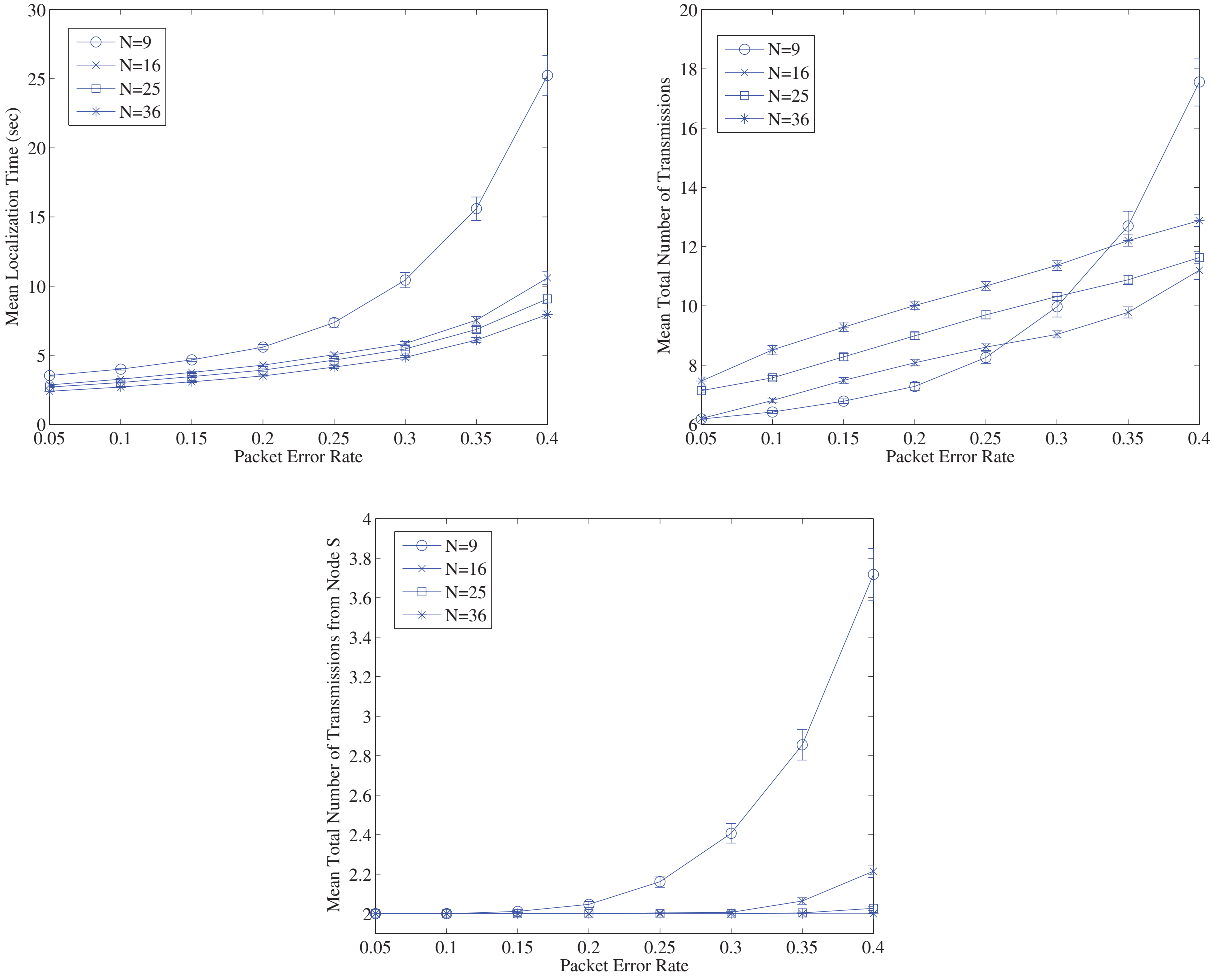

Fig. 7. Evaluation of localization latency and efficiency for E-UPS (X=1000, z_s = 50).

p	% reduction in E[T] with E-UPS				% reduction in E[n_{total}] with E-UPS				% reduction in (E[n_s]) with E-UPS			
	N=9	N=16	N=25	N=36	N=9	N=16	N=25	N=36	N=9	N=16	N=25	N=36
0.05	25.60	31.50	29.12	33.27	-16.96	-17.34	-35.07	-41.22	-39.18	-39.18	-39.18	-39.18
0.1	48.02	51.19	50.86	53.65	9.98	4.50	-6.23	-19.48	5.48	5.48	5.48	5.48
0.15	60.76	63.51	63.77	65.82	29.40	22.09	13.83	3.37	34.82	35.21	35.21	35.21
0.2	71.51	74.71	75.03	76.45	47.31	41.53	34.94	27.54	57.93	58.90	58.90	58.90
0.25	76.62	81.41	81.59	82.68	58.54	56.80	51.33	46.44	71.58	73.65	73.70	73.70
0.3	79.78	86.84	86.82	87.64	66.42	69.56	65.25	61.71	80.35	83.62	83.67	83.67
0.35	82.55	90.20	90.42	91.02	73.05	79.25	76.91	74.10	86.39	90.16	90.45	90.47
0.4	83.53	91.96	92.62	93.18	76.44	84.97	84.39	82.72	89.59	93.80	94.32	94.40

TABLE II

PERCENTAGE GAIN IN LOCALIZATION PERFORMANCE WITH E-UPS OVER UPS (X=1000, z_s = 50).