SEAL: Self-adaptive AUV-based Localization for Sparsely Deployed Underwater Sensor Networks

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***Abstract*— In this paper, we propose a Self-adaptive AUV-based Localization (SEAL) scheme, which is specifically designed to provide network-wide localization service to sensor nodes in sparsely deployed Underwater Sensor Networks (UWSN) using a high-speed Autonomous Underwater Vehicle (AUV). Even though the sparse nature of node deployment in UWSN is cost-effective, it creates a new challenge for the existing UWSN localization schemes. Moreover, due to the effect of passive node mobility owing to oceanic waves and currents, the network topology experiences partitioning. In such a sparse deployment scenario, the existing static anchor-based schemes of node localization exhibit low localization coverage, high localization error, and high message overhead. On the contrary, mobile anchor-based schemes are able to maintain low message overhead. However, these schemes achieve low localization coverage only or result in higher average energy consumption. In SEAL, we excogitate a simple and *self-adaptive* scheme, which empowers the AUV to select deployment-aware transmission range and maintain energy-efficiency. Simulations in NS-3 indicate that SEAL achieves significantly improved localization coverage while maintaining the energy-efficiency of the AUV when compared to the schemes from the existing literature that were considered as benchmarks in this study.**

***Index Terms*—AUV-based Localization, Underwater Sensor Networks, Self-adaptation, Node Mobility, Sparse Deployment**

I. Introduction

A. Motivation

Localization of sensor nodes is a fundamental problem in event-driven networks such as UWSNs [1], [2]. However, considering the unsuitability of Global Positioning System (GPS) in underwater environments, and the effect of passive node mobility resulting from underwater currents, the problem of localization is challenging in such environments [3], [4]. Location information is crucial for various applications such as target tracking [5], [6], location-based routing protocols [7], [8], topology management [9], and environmental monitoring [10] and pollution control in any sensor network. Also, the sensed data in these applications can be analyzed meaningfully, if they are tagged with location information. However, the inherent challenges of the underwater medium makes the problem even more interesting than in the terrestrial environment [1], [11]–[14]. GPS-based systems are not well-suited for use in underwater environments due to severe attenuation of radio frequency signal, and the energy-consuming nature of these systems. To mitigate the attenuation problem of using radio frequency, the underwater nodes communicate using acoustic signals.

Instead of using GPS to determine the unlocalized nodes' locations, the existing underwater localization schemes exploit the spatio-temporal relationship between an unlocalized node and few reference nodes. However, UWSNs are often deployed sparsely to reduce the overall implementation cost [15]. Furthermore, sparse node deployment is usually practiced in some UWSN applications such as oceanographic data collection, submarine tracking, and surveillance. In such scenarios, the sensor nodes lack the presence of required number of reference nodes in their transmission range to get successfully localized. Moreover, due to the application requirements, sometimes the sensor nodes are deployed in deeper parts of ocean. In such problem scenarios, the use of AUVs eases data collection and localization holistically. Also, such infrastructure can help in relieving the sensor nodes off major computation and communication overhead. The sensor nodes can use lesser transmission power for information dissemination through the AUVs. Also, compared to the surface anchor-based localization schemes, the AUV-based schemes are successful in node localization in upward refracting environments. AUV-based UWSN architecture have been proposed in the existing literature (e.g. [16]–[18]). Apart from these, the effect of passive node mobility leads to frequent network partitioning, thereby worsening the already challenging problem scenario. Undoubtedly, mere exploitation of spatio-temporal relation between different sensor nodes does not help in localization in such scenarios. Thus, using an AUV to aid the localization process in such scenarios provides better localization coverage as well as helps in maintaining the energy-efficiency of the deployed nodes. However, using a high-speed AUV has certain challenges such as deciding the trajectory of the AUV, addition of costly sensor for determination of precise location for beacon messages.

The localization schemes existing in the literature are typically classified in two different categories – *anchor-based* and *anchor-free*. In *anchor-based* schemes, special types of nodes, named as *anchors*, are used to aid the localization process.

Depending on the type of anchor, the anchor-based scheme are classified as – *static* or *mobile*. In *static anchor-based* schemes [2], [19]–[23], the surface anchors are the initial source of beacon messages, and they help the near surface nodes to get localized. Consequently, the beacon messages flow iteratively throughout the network. In sparse and partitioned scenarios, these *static anchor-based* schemes fail due to the unavailability of the reference nodes. On the other hand, in the *mobile anchor-based* [24]–[28] schemes, the mobile anchor such as AUVs or Dive'N'Rise (DNR) is employed as the beacon provider to assist the localization process. In this regard, the use of AUVs as anchors to localize underwater nodes renders some advantages over the other schemes. *First*, the flexibility of movement of the AUVs facilitates their roles as anchors in mobile environments. *Secondly*, the use of AUVs reduces the complexity of deploying anchor nodes under water, and each AUV is capable of replicating the functionalities of many anchor nodes. *Third*, AUVs are enriched with more computation capability, and battery power is not a limitation unlike the sensor nodes. Also, most of these schemes utilize the 'silent' messaging technique, which renders energy-efficiency to the sensor nodes.

On the other hand, the use of AUVs introduces few limitations to the scheme also. The existing pieces of literature on AUV-based localization consider only fixed and preplanned trajectory [24]–[28]. As a result, the localization success of the sensor nodes becomes greatly dependent on the AUV trajectory, as the nodes present in the vicinity of the trajectory are only localized. Also, reliance on a fixed trajectory may lead to fluctuated performance in terms of localization success, specifically in sparse and disjoint UWSNs. Therefore, it is necessary to design a scheme which can achieve high localization coverage. In other words, the schemes should be capable of providing network-wide localization coverage to the sensor nodes specifically in sparse UWSNs.

B. Contributions

In this paper, we propose a Self-adaptive AUV-based Localization (SEAL) scheme, specifically for use in sparse UWSN scenarios. We propose to use a high-speed AUV as location beacon provider such that the AUV is able to transmit location beacons at significantly spaced points, which in turn enhances the chances of forming a robust virtual anchors plane to avoid incorrect realization of flip ambiguities. From the ocean surface, the AUV descends to the specific depth of interest, and proceeds throughout the network following its trajectory. On the other hand, the sensor nodes float in the 3D space of water, and move with the effect of passive node mobility. In the proposed scheme, the sensor nodes, apart from getting localized by receiving location beacons, inform the AUV about their neighbor details. For this, the sensor nodes also need to 'actively' transmit messages to the AUV. This setting costs the sensor nodes higher energy compared to the schemes employing 'silent' messaging. However, this trade-off in average energy consumption of the sensor nodes helps the network in attaining higher localization coverage overall. Based on the information provided by the sensor nodes, the AUV decides its transmission range, and updates it accordingly. Thereafter, we cite this scheme as *self-adaptive*, as the AUV *itself* decide the transmission range *adaptive* to the deployment context. The sensor nodes, upon receiving the required number of beacon messages (for example, in trilateration, three beacon messages[1] are required for successful localization), localizes themselves. Thus, cooperation between the sensor nodes and the AUV is beneficial for both the entities. In summary, the specific *contributions* of this work are cataloged as follows.

- We excogitate a *self-adaptive* scheme, which empowers an AUV to intelligently adjust the transmission range in a sparse deployment scenario. This enhances power-awareness to the AUV while resulting in improved network-wide localization coverage.
- We propose a solution for the sensor nodes to inform the AUV about the deployment-context, and in turn, help localizing more unlocalized nodes.

The remainder of the paper organization is as follows. In Section II, we review the related works on underwater localization briefly. Section III describes the system model in detail. The proposed solution scheme is elaborated in Section IV. We present the performance evaluation of the proposed scheme in Section V. Finally, we conclude the paper in Section VI, while citing directions for future research.

II. Related Works

In recent years, the problem of node localization in UWSNs is studied from various respects [3], [4]. The proposed scheme, SEAL, is related to the *mobile anchor-based* category, as it employs an AUV as beacon provider. Therefore, in the following, we discuss such *mobile anchor-based* schemes only.

Dive'N'Rise localization (DNRL) [24] is one famous mobile anchor-based localization scheme. DNRL uses multiple Dive'N'Rise (DNR) beacons, which dive and rise along the ocean column for broadcasting location information. The ordinary nodes listen to these beacons and get localized. Although, the utilization of 'silent' messaging makes this scheme energy-efficient, the slow speed of the mobile beacons indirectly increases the location estimation error in the presence of node mobility. The overall cost of the network increases as DNRL requires large number of DNR beacons. Also, time-synchronization between the underwater nodes and the DNR beacons is required. DNRL was extended to Multi-Stage Localization (MSL) [29], which was proposed to increase the localization coverage. In MSL, the localization process is completed in two phases – DNR-based phase and iterative phase. First, few nodes are localized with the help of the DNR beacons, and in the next phase, the once localized nodes act as references to the rest of unlocalized nodes. However, the use of multi-stage localization increases the energy consumption of the nodes compared to DNRL. Also, time-synchronization between the nodes is required due to the use of ToA in one way ranging.

[1]If the nodes have knowledge about their z-coordinate, only three beacon messages are required for successful localization

Erol *et al.* [25] proposed the use of AUV, instead of DNR-beacons, to aid the localization process in their proposed scheme named AUV-Aided Localization (AAL). An AUV moves throughout the network, while maintaining its trajectory, by using the technique called Dead-reckoning [30], [31]. Initially, the AUV broadcasts 'wake-up messages periodically. On hearing this, the unlocalized sensor nodes send a 'request message to the AUV, and receives a reply from the AUV about its location. During this process, the intermediate distance between the AUV and the sensor nodes is calculated using the ToA (two-way ranging) method. After receiving three such location beacon, a sensor node computes its location using lateration. AAL does not need time-synchronization between the nodes. However, the sensor nodes are assumed to be stationary in their proposed scheme. Moreover, energy consumption of the sensor nodes increases as both the entities — the AUV and the sensor nodes — take part in two-way communication to exchange messages between them. Mirza et al. proposed Collaborative Localization (CL) [32] for UWSNs specifically deployed for serving a data collection application. In the localization architecture, the authors consider two types of nodes present, namely – 'profilers and 'followers. The authors also assume that both of these nodes descend in water, however, the 'profilers descend faster than the 'followers. Also, both types of nodes descend, while maintaining the same speed. Thus, the movement is in the same frame. The intermediate distance between these two types of nodes is calculated periodically using the ToA method. Thus, the future locations of the 'followers can be estimated based on the future locations of the 'profilers. However, the demerit of this scheme is the synchronization requirement between the 'profilers and the 'followers. Moreover, CL is limited to a specific network architecture.

Directional antenna powered AUV is deployed for the purpose of node localization by Luo et al. in Using Directional Beacons for Localization (UDB) [33] and Localization with Directional Beacons (LDB) [26]. In both UDB and LDB, the sensor nodes receive the location beacon 'silently' from a AUV, which is powered with a directional antenna. However, UDB was proposed for 2D UWSNs, and it is extended to its 3D counterpart in LDB. A sensor node estimates its abscissa, by averaging the *first-heard* and the *last-heard* beacon points. However, the authors assumed the sensor nodes to be stationary, as they are tucked with the elastic chain's pull force. In LDB, the AUV needs to traverse the network twice to localize the sensor nodes, because of the use of directional transceiver. On the other hand, in UDB, the AUV has to hover upon the area of the deployed nodes. In another localization scheme, named Multi-stage AUV-aided localization (MSAL) [27], the AUV moves along a fixed path to localize the stationary sensor nodes. In the first stage, nodes localize themselves by 'silently' receiving messages, and in the second stage, these localized nodes help the other localized nodes to get localized. However, the authors assume time-synchronization between the AUV and the sensor nodes. Also, this scheme is proposed only for the stationary UWSNs with shallow water depth.

Localization with a Mobile Beacon (LoMoB) [34] is another mobile anchor based localization scheme, in which, the mobile beacons powered with omni-directional transceivers broadcast the location information periodically. First, few potential candidate locations are found from the projected coordinates of the mobile beacon. Then, the location of any unlocalized sensor node is determined by computing the weighted mean of the potential beacon locations. However, the authors do not consider the presence of passive node mobility in the deployment. Also, the mobile beacon moves by following the Random Way Point (RWP) mobility model. Localization in 3-dimensional underwater scenario, where sensor nodes are affected by passive mobility, was proposed by Ojha and Misra [28]. This scheme also considers AUVs moving along a pre-defined trajectory, and sensor nodes localizing themselves after receiving three location beacons from the three different AUVs. Although, the use of three AUVs increases the deployment cost, employing silent messaging increases the energy efficiency of this scheme. In this scheme, time-synchronization between the nodes is not required. However, AUVs are considered as time-synchronized. In *Mobile AUV-aided Localization Scheme* (*MobiL-AUV*) [35], the authors employ three different AUVs to provide location beacons and aid the localization scheme. The AUVs get their coordinates at the surface, and then they dive vertically through the deployed nodes. The nodes use spatial correlation to predict their mobility, and this helps in minimizing their localization error.

In all these schemes, the trajectory of the AUVs are assumed to be known *a priori*. This limits the performance of these schemes in sparse UWSN deployment-contexts.

III. System Model

A. Network Architecture

We consider that the sensor nodes (N) are deployed in a 3D UWSN, represented as a graph $G(N, E(t))$. Here, $E(t)$ denotes the set of edges in the network at time t. The network architecture is shown in Figure 1. The nodes move with the effect of passive node mobility generated due to underwater currents. No surface localized anchor nodes are considered. A low-cost pressure sensor is attached onboard in the architecture to calculate the depth of each node. For a node i, the set of its neighbors at time t is denoted by $Nbr_i(t)$. A sensor node i has a fixed communication range of r_i for a transmission power level p_i. Any node j is a neighbor of node i or $j \in Nbr_i(t)$ in the network graph $G(N, E(t))$ *iff* $(i, j) \in E(t)$, and the distance between i and j is $d_{ij} \leq r_i$ $\forall i, j \in N$. We also consider that N_l and N_{ul} denote the set of localized and unlocalized nodes, respectively.

The AUV, on the contrary, is powered with both acoustic and RF communication facility. Initially, the AUV computes its initial coordinate using GPS, while it is on the water surface, and then it dives to the specified depth of interest. The AUV is capable of maintaining its trajectory through the network using the *dead-reckoning* technique [30], [31]. In Figure 1, we mark the horizontal plane of movement for the AUV. We also assume that the AUV is capable of dynamically changing its transmission power. Let, $p_a(t) \in P_a$ be the transmission power of the AUV at time t. P_a and R_a denote

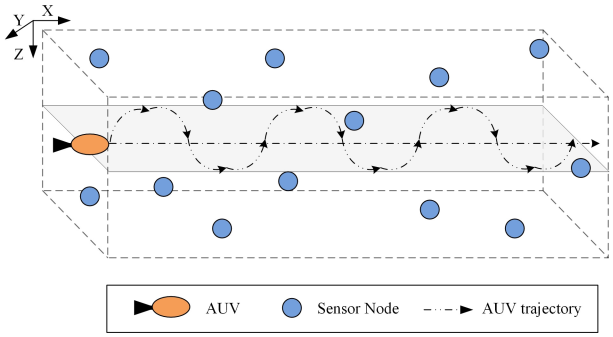

Fig. 1: Deployment scenario of SEAL.

TABLE I: List of Symbols

Symbol	Meaning
N	The set of all deployed nodes
N_l	The set of the localized nodes
N_{ul}	The set of the unlocalized nodes
$E(t)$	The set of the edges in the network
$Nbr_i(t)$	The set of the neighbors of node i at time t
$Nbr_a(t)$	The set of neighbors of AUV a at time t
Nbr_i^{max}	Typical value of maximum number of neighbors a node can have
p_i	The transmission power of node $i \in N$
r_i	The transmission range of node $i \in N$
$p_a(t)$	The transmission power of AUV a at time t
$P_a(t)$	The set of available transmission power levels of AUV a at time t
$r_a(t)$	The transmission range of AUV a at time t
$R_a(t)$	The set of available transmission range levels of AUV a at time t
r_{min}	Minimum transmission range of AUV a
r_{max}	Maximum transmission range of AUV a
$W_i(t)$	The set of total residual energy of node $i \in N$ at time t
$\mathcal{N}_{eff}(t)$	The effective number of neighbors of AUV a at time t
$\mathcal{P}(\cdot)$	Profit of AUV a
$\mathcal{A}(\cdot)$	Ability of AUV a
$r_{req}(i,t)$	The required transmission range of AUV a at time t
t_{delay}	Localization delay
d_{ij}	Distance between node i and j

the set of available transmission power and range, respectively. Also, $P_a = [p_1, p_2, \cdots, p_\kappa]$, where κ denote the number of transmission power levels. Accordingly, the communication range of the AUV also changes, as $p_a(t)$ and $r_a(t)$ possess an one-to-one bijective mapping, i.e., $f : P_a \to R_a$. The neighborhood of the AUV is subject to change frequently due to its movement, and also the dynamic changes in the transmission range. Let, the set of neighbors of the AUV at time t be denoted by $Nbr_a(t)$, when $p_a(t)$ is the transmission power at instant t. The minimum and maximum values of the transmission range are represented as $r_{min} = \inf(R_a)$ and $r_{max} = \sup(R_a)$. Table I lists the symbols used in the paper.

B. Assumptions

The following list describes the assumptions considered in this work.

- The sensor nodes know their depth value with the help of a pressure sensor.
- The sensor nodes are not time-synchronized between themselves, or with the AUV.
- The sensor nodes and the AUV are capable of calculating inter-node and node-AUV distance using Received Signal Strength Indication (RSSI) or Time Difference of Arrival (TDoA) technique.
- The AUV is able to change its transmission range.
- The sensor nodes do not have the facility to change their transmission range.

IV. Self-adaptive AUV-based Localization

The overall mechanism of node localization in the proposed scheme, Self-adaptive AUV-based Localization (*SEAL*), constitutes of two parts — the procedure executed in the sensor nodes, and the procedure executed in the AUV. Consequently, we explain each part in detail in Sections IV-A, and IV-B, respectively. The sensor nodes are assumed to be unlocalized, and they get localized after receiving the location beacons from the AUV. On the other hand, the AUV receives its coordinate using GPS while it is on the water surface. Then, it dives down vertically to a certain depth, where it follows its trajectory in between the nodes in the network.

The AUV follows its trajectory and continue to interact with the sensor nodes. The sensor nodes informs the AUV about their neighborhood deployment details. Based on the information provided by the sensor nodes, the AUV decides its transmission range, and updates it accordingly. Thereafter, we cite this scheme as *self-adaptive*, as the AUV *itself* decide the transmission range *adaptive* to the deployment context. The following sections discusses the procedures followed by the AUV and the sensor nodes in detail.

A. Procedure for the sensor nodes

Prior to receiving beacons from the AUV, or informing the AUV about their presence, the sensor nodes communicate among themselves. The overall procedure followed by the sensor nodes is named as *Neighbor Information Dissemination and Localization* (*NIDL*). NIDL comprises of two phases — *Neighbor Finding*, and *Location Estimation*. The phase, Neighbor Finding, is executed before the AUV starts its journey. After receiving the location beacons from the AUV, the nodes execute the phase, Location Estimation, to find their respective locations. Each of these phases is elaborated below.

1) Neighbor Finding: In this phase, the unlocalized sensor nodes interchange few information among themselves. Each node broadcasts an 'Info' message containing its identifier (id), and the depth information. The nodes, on receiving the 'Info' message, update their information about the neighbors. Then, the nodes respond back to the sender with their own 'Info' message, if they did not send the 'Info' message earlier. The waiting time of a node i, for receiving all its neighbor's information, is denoted by $t_{wait}(i) = \frac{2 \times r_i}{v_{sound}} + Nbr_i^{max} \times t_{trans}$, where r_i is the transmission range of any node, v_{sound} is the sound velocity, Nbr_i^{max} is the maximum number of neighbors a node can have and t_{trans} is the time required to transmit the 'Info' message. Typically, the value of Nbr_i^{max} can be set by the system developer with a mechanism to update it in future iteration of localization as, $Nbr_i^{max} = \max(Nbr_i^{max}, Nbr_i(t))$. Here, the rationale for this formula is that the sender node needs to wait for a reasonable amount of time such that the responses from all possible neighbors can be received. Therefore, we consider the time for the acoustic signal to travel to the furthest node (at r_i distance) and back, and the time for the Nbr_i^{max} neighbors to send the 'Info' message.

It is noteworthy to mention that messages may be lost due to collision at the MAC layer. In this work, our primary focus is to devise a localization scheme that corresponds to the application layer. The underlying MAC layer protocol takes care of the issues with the collision and retransmission. In this work, we utilize CW-MAC [36] protocol at the MAC layer that implicitly addresses the issues with collision. Based on the neighbor information received at the MAC layer, the proposed scheme computes the deployment context and it is further used in the localization process. Therefore, we limit our discussion on the issues with message collision and retransmission in this work.

After receiving the neighbor information ($Nbr_i(t)$), the node i performs few computations based on the following information — *number of neighbors* ($|Nbr_i(t)|$) and *maximum distance* ($d_{ij}^\star$) *with its neighbor* j. For each 'Info' message received, node i computes $d_{ij}^\star = \max_j d_{ij}$ for all of its neighbors such that $\forall j, k \in Nbr_i(t), k \neq j, d_{ij} > d_{ik}$. Consequently, the nodes inform the AUV using 'InfoAUV' message citing the number of neighbors ($|Nbr_i(t)|$) and the distance to the farthest neighbor ($d_{ij}^\star$).

2) Location Estimation: The AUV traverses through the network and periodically broadcasts location beacons. Each of these beacons contains the current location of the AUV, tagged by a sequence number. The sequence number field is updated with the progress of the AUV. Two location beacons are distinguished by any node using the sequence number. After receiving the required number of beacons ($n_{ref}|_{max}$), a node calculates its own location. The required number of beacons in this case is three, as we apply trilateration for calculating a node's location from three reference nodes. Let, the three positions of the AUV from which it sends the location beacons be denoted by (x_1, y_1, z_1), (x_2, y_2, z_2), and (x_3, y_3, z_3). We assume that d_1, d_2, and d_3 denote the distance between the AUV and the sensor node at three beacon locations, respectively. As mentioned in the list of assumptions in Section III-B, d_1, d_2, and d_3 can be calculated by applying RSSI [37] or TDoA [38] technique. Based on these information, the location of the unlocalized sensor node is obtained by applying trilateration.

In Algorithm 1, we present NIDL, the procedure followed by the sensor nodes. In NIDL, we also consider the residual battery status $W_i(t)$ of the sensor nodes ($i \in N$) during the procedure. The sensor nodes consider their residual battery status, and perform any message transmission after checking whether the residual battery energy is higher than the threshold level (W_{th}) or not.

The underwater nodes apply Trilateration after receiving the required number ($n_{ref}|_{max}$) of beacons. However, it may happen that Trilateration is not successful using these set of beacons. On the other hand, any unlocalized node receives more than three beacons from the AUV. Thereby, to leverage

Algorithm 1: NIDL: Neighbor Information Dissemination and Localization for Unlocalized Sensor Nodes

```
input : N, r_i, p_i, {W_i(t)}_{i∈N}.
output: Localization delay t_loc.
if 'Info' Send = false and W_i(t) > W_th then
    Broadcast 'Info' message with node ID i;
for Each 'Info' message received from node j ∈ N to node i ∈ N do
    Add node j to Nbr_i(t);
    Update maximum distance with its neighbor, d*_ij;
for Each beacon message received do
    Calculate distance between the node and AUV, d_ia;
    Update the number of references nodes, n_ref(i);
    if Number of beacons received = 1 then
        t_init ⟵ t_now;
        if 'InfoAUV' Send = false and W_i(t) > W_th then
            Send message 'InfoAUV' to AUV with node
            ID i, z_i, d*_ij, and number of its neighbor
            |Nbr_i(t)|;
    if Number of beacons received = n_ref|_max then
        Apply Trilateration;
        Return t_loc ⟵ t_now − t_init;
```

the best out of this situation, the node checks for localizability with different set of beacons from the received beacons. In NIDL, we consider this case when a node is unable to compute location with the help of minimum number of beacons. Thereby, the node retries Trilateration with different set of beacons. This process can increase the localization coverage of the proposed scheme, however, at the cost of increased localization delay. Thus, two user defined parameters n_{retry} and $n_{retry}|_{max}$ are introduced to control the number of retries.

B. Procedure for the AUV

The AUV lowers its position through the ocean column to reach the specific depth of interest. We assume that the starting point of AUV's trajectory is located at the middle of the deployment region. Let, the dimensions of the 3D UWSN be $l \times b \times h$. So, in this case, the AUV lowers its position to the coordinate $(0, b/2, h/2)$, and starts *dead-reckoning*. From this position onwards the AUV periodically broadcasts beacon messages containing its coordinates. The AUV is required to be of high-speed as the underwater nodes are also mobile. With high-speed, the AUV will be able to transmit location beacons at significantly spaced points. It will enhance the chances of forming a robust virtual anchors plane [39] such that to avoid incorrect realization of flip ambiguities.

The AUV, initially interacts with the deployed nodes to access the deployment context from the 'InfoAUV' messages send by them. Based on the available information, the AUV intelligently selects an optimal transmission range suitable for the deployment. Thereby, the AUV minimizes its energy consumption while being able to send beacons to the underwater nodes. To dynamically enhance the localization coverage with minimum energy consumption, we propose a scheme named *Sparse-Aware Transmission Range Selection* (*STARS*), for the AUV. In this scheme, the AUV intelligently selects the transmission range $r_a(t) \in R_a$, while the beacon sending interval (t_b) is kept constant. We describe the STARS scheme in Section IV-B1. Prior to that, we define few terms which are used in the consecutive sections.

Definition 1. *The effective number of neighbors ($\mathcal{N}_{eff}(t)$) of the AUV at time t refers to the extended set of nodes which includes all the neighbors of AUV's direct neighbors for the transmission range of $r_a(t) = r_{max}$. The rationale for considering this parameter is to estimate the number of nodes, from the current deployment context, which can be communicated with a location beacon by increasing the transmission range of the AUV as $r_a(t) = r_{max}$. This number can be calculated by subtracting the number of neighbors of the AUV from the total number of neighbors ($\sum_{i\in Nbr_a(t)} |Nbr_i(t)|$) of the AUV's direct neighbors ($\forall i \in Nbr_a(t)$).*

$$\mathcal{N}_{eff}(t) = \sum_{\substack{i\in Nbr_a(t)\\ r_a(t)=r_{max}}} |Nbr_i(t)| - |Nbr_a(t)|$$

where, $|Nbr_a(t)|$ is the number of 'InfoAUV' messages received by the AUV, and thus, it is the number of neighbors of the AUV at time t. The total number of neighbors of AUV's neighbors is computed as $\sum\limits_{i\in Nbr_a(t)} |Nbr_i(t)|$.

Definition 2. *The Ability of an AUV ($\mathcal{A}(r,t)$) is defined as the ratio of the number of nodes that can be localized ($|Nbr_i(t)|_{i\in Nbr_a(t)}$) with its current transmission power $p_a(t)$ (for $r = r_a(t)$), and the effective number of neighbors ($\mathcal{N}_{eff}(t)$).*

$$\mathcal{A}(r,t) = \sum_{\substack{i\in Nbr_a(t)\\ r=r_a(t)}} \frac{|Nbr_i(t)|_{i\in Nbr_a(t)}}{\mathcal{N}_{eff}(t)}$$

Here, 'Ability' refers to the localization ability of the AUV. The rationale is to estimate the potential effect of AUV's change of transmission range on localization of the deployed nodes. Using this parameter, we can transform the transmission range value to a ratio which denote the total number of nodes which can be localized by the AUV. Consequently, the AUV computes the profit associated with the selection of a transmission range. Furthermore, the AUV can dynamically choose the transmission range for broadcasting the location beacon to the nodes according to the deployment context.

1) Sparse-Aware Transmission Range Selection for the AUV: Algorithm 2 presents the scheme followed by the AUV to dynamically select the transmission range ($r_a(t)$) for the next beacon message broadcast. The AUV includes the information provided by the sensor nodes from the received 'InfoAUV' message. The message format and its contents are described in Section IV-C. The AUV adds each node from which it received the 'InfoAUV' message to the list recording its set of neighbors at time t. From each message received from node i, the AUV computes the distance (denoted as d_{ij}) with the farthest neighbor, say j. Also, the AUV calculates the distance with node i, d_{ai}. Then, the AUV estimates the required transmission range for localizing the farthest neighbor, as shown in Equation 1. In Lemma 1, we prove that when the transmission range of the AUV is set to $r_{req}(i,t)$, then the AUV can cover node j, which is the farthest neighbor of node i. Subsequently, in Lemma 2, we show the relation between the required transmission range of AUV and the transmission range of a deployed node. Thus, we have,

$$r_{req}(i,t) = d_{ai} + \max_j d_{ij} \qquad \forall i \in Nbr_a(t),\ j \in Nbr_i(t) \tag{1}$$

For each transmission range $r \in R_a$ (number of such levels is κ), the AUV then calculates the *Ability* $\mathcal{A}(r,t)$ at time t. Based on the satisfiability of the condition, $r \geq r_{req}(i,t)$, *Ability* is updated according to Equation 2.

$$\mathcal{A}(r,t) = \mathcal{A}(r,t) + \sum_{i\in Nbr_a(t)} \frac{|Nbr_i(t)|}{\mathcal{N}_{eff}(t)} \tag{2}$$

The *Ability* of the AUV is higher for higher transmission range (or power). However, with increase in the communication range, the AUV consumes more energy, which reduces the residual battery power. Thus, we take into account the *Profit* $\mathcal{P}(\cdot)$ of the AUV to decide the transmission range $r_a(t) \in R_a$.

The AUV dynamically selects its transmission range based on the information received from the sensor nodes $i \in Nbr_a(t)$. A new transmission range ($r_a(t)$) is selected such that the *Profit* of the AUV is maximized. The *Profit* of the AUV is directly proportional to its *Ability* for localizing the sensor nodes with transmission range $r_a(t)$ at time t. Mathematically,

$$\frac{\delta\mathcal{P}}{\delta\mathcal{A}} \geq 0 \tag{3}$$

Also, with increase in the transmission range, the AUV's energy consumption ($\mathcal{E}_a$) increases due to the increase in its transmission power to $p_a(t)$. Thus, the *Profit* of the AUV is non-increasing and concave for selecting a higher transmission range.

$$\frac{\delta\mathcal{P}}{\delta\mathcal{E}_a} < 0 \tag{4}$$

Definition 3. *For any transmission range $r = r_a(t)$ at time t, we define Profit ($\mathcal{P}(r,t)$) of an AUV as the difference between 'the utility gain from the increase of Ability', and 'the loss due to increase of energy consumption'. Thus,*

$$\mathcal{P}(r,t) = \mathcal{A}(r,t) - e^{-\frac{r_{min}}{r}} \tag{5}$$

where $r, r_{min} \in R_a$ and $r_{min} = \inf(R_a)$. Here, the goal is to enable the AUV to estimate the effect of the change in the transmission range. As a result of the increase in the transmission range, the AUV can aid the localization process of more number of nodes. However, the tradeoff here is that increase of transmission range results in increase of the energy consumption of the AUV. Therefore, using this formulation, the AUV can gauge the potential of choosing a transmission range by collating both these effects.

The AUV selects the transmission range $r = r_a(t)$, which maximizes the *profit* for time t. Thus, the AUV is capable of selecting the transmission range according to the deployment context. Mathematically, using Equation (2) and (5), the range of AUV is computed as,

$$r_a(t) = \underset{r \in R_a}{\arg\max}\, \mathcal{P}(r,t) \tag{6}$$

$$\text{or, } r_a(t) = \underset{i \in Nbr_a(p(t))}{\arg\max} \sum_i \left(\frac{|Nbr_i(t)|}{\mathcal{N}_{eff}(t)} - e^{-\frac{r_{min}}{r}} \right) \tag{7}$$

Lemma 1. *Node $j \in Nbr_i(t)$ is in the transmission range of the AUV a, when the transmission range ($r_a(t)$) of the AUV is set to $r_{req}(i,t) = d_{ai} + \max_j d_{ij}$, where $i \in Nbr_a(t)$ for $p_a(t)$.*

Proof: Let $j \in Nbr_i(t)$ is the furthest neighbor of node i, and $r_{req}(i,t)$ is the required transmission range for satisfying the condition that j is in the transmission range of the AUV a. As shown in Figure 2, we assume that there is a triangle with vertices a, i and j. Following the triangular inequality on Δaij, we can conclude that $d_{ai} + d_{ij} > d_{aj}$. Clearly, we need to satisfy the following condition: $r_{req}(i,t) > d_{aj}$.

Hence, the maximum required range for covering node j from the AUV is $r_{req}(i,t) = d_{ai} + \max_j d_{ij}$. ∎

Lemma 2. *The conditional relationship between the AUV's and node's transmission range, such that the farthest neighbor (j) of the farthest neighbor (i) of AUV (a) is inside the new transmission range of the AUV, is: $r_a|_{max} = 2 * r_i$, where $r_a|_{min} = r_i$ and $r_{req}(i,t) = d_{ai} + \max_j d_{ij}$.*

Proof: From Lemma 1, we know that the required transmission range of AUV such that the furthest neighbor (j) of the furthest neighbor (i) of AUV (a) is $r_{req}(i,t)| = d_{ai} + \max_j d_{ij}$.

As mentioned in Section III, we also assume that the AUV is capable of dynamically changing its transmission range, and minimum transmission range is $r_a|_{min} = r_i$.

Therefore, the maximum required transmission range of the AUV is,

$$\begin{aligned}
r_a|_{max} &= r_{req}(i,t)|_{max} \\
&= d_{ai}|_{max} + \max_j d_{ij} \\
&= d_{ai}|_{max} + r_i \qquad \text{assuming } r_i = \max_j d_{ij} \\
&= r_a|_{min} + r_i \qquad \text{as } r_a|_{min} = d_{ai}|_{max} \\
&= 2 * r_i \qquad \text{as } r_a|_{min} = r_i
\end{aligned}$$

Hence, proved. ∎

C. Message formats

The different messages that are communicated between the AUV and the sensor nodes are shown in Figure 3. Overall, in SEAL, three types of messages are communicated – 'Info', 'InfoAUV', and 'Location Beacon'. 'Info' messages are exchanged among the sensor nodes for the purpose of updating the neighbor information. Based on the information from the neighbors, a node i updates its information about the maximum distance from a neighbor (d_{ij}) and the number of neighbors ($|Nbr_i(t)|$). These information are encapsulated in

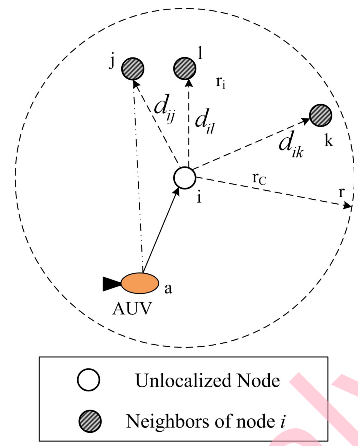

Fig. 2: Interactions between the AUV and nodes to calculate $r_{req}(i,t)$.

Algorithm 2: STARS: **S**parse-Aware **T**ransmission **R**ange **S**election for the AUV

input : N, $Nbr_a(t)$, P_a, $\{Nbr_i(t)\}_{i \in Nbr_a(p(t))}$.
output: Transmission Range $r_a(t)$.
for *Each 'InfoAUV' message received from node $i \in N$* **do**
  Add node i to $Nbr_a(t)$;
  Calculate the distance between node i and AUV, d_{ai};
  Get the distance d_{ij} of the farthest neighbor $j \in Nbr_i(t)$ from the 'InfoAUV' message. $d_{ij} = d^\star_{ij}$;
  Calculate the *required transmission range*, $r_{req}(i,t) \longleftarrow d_{ai} + \max_j d_{ij}$;
Calculate the *effective number of neighbors* of the AUV, $\mathcal{N}_{eff}(t) \longleftarrow \sum_{i \in Nbr_a(t)} |Nbr_i(t)| - |Nbr_a(t)|$;
for *Each $r \in R_a$* **do**
  for *Each $i \in Nbr_a(t)$* **do**
    if $r \geq r_{req}(i,t)$ **then**
      Update the *Ability* of the AUV for transmission range r as $\mathcal{A}(r,t) \longleftarrow \mathcal{A}(r,t) + \frac{|Nbr_i(t)|}{\mathcal{N}_{eff}(t)}$;
Calculate profit $\mathcal{P}(r,t) \longleftarrow \mathcal{A}(r,t) - e^{-\frac{r_{min}}{r}}$;
for *Each $r \in R_a$, and $\forall r^\star \in R_a$, $r^\star \neq r$* **do**
  if $\mathcal{P}(r,t) > \mathcal{P}(r^\star,t)$ **then**
    Update $r_a(t) \longleftarrow r$;

the 'InfoAUV' packet, and are sent to the AUV. The AUV decides the required transmission range which provides maximum profit. Then, the AUV broadcasts the location beacons, each of which contains the information about the sequence number and the AUV's location.

V. Performance Evaluation

A. Simulation Settings

We perform the simulation of the proposed scheme using NS-3 (http://www.nsnam.org/). The number of nodes was

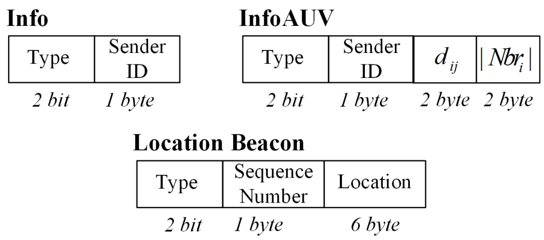

Fig. 3: Message formats used in SEAL

varied from 10-50 in the deployment region of 2500 $m \times 2500$ $m \times 2500$ m. In the simulations, the AUV was considered to move by following a sinusoidal trajectory and spiral trajectory. However, other trajectory patterns of the AUV could also be considered without affecting the inferences. In the intense of brevity of the paper, we presented results with only one type of trajectory. For the transmission range of the AUV, we considered $R_a = [1000m, 1500m, 2000m]$, where the number of different transmission range levels $\kappa = 3$. In the simulations, we set `UanPhyGen` as the physical layer of the AUV and the nodes in NS-3. For modelling the acoustic propagation, we consider the Thorp's propagation model (TP model) [40] and Deep sea propagation model (DSP model) [41]. In the Thorp model, considering the spreading and absorption losses, the transmission loss (TL) is expressed as,

$$TL = 10 \times \log r + \alpha \times r \times 10^{-3} \quad (8)$$

Similarly, for the deep sea acoustic propagation, the transmission loss (TL) due to spreading and absorption losses are expressed as,

$$TL = 20 \times \log r + \alpha \times r \times 10^{-3} \quad (9)$$

where r and α denote the transmission range (in $meter$) and the absorption coefficient (in dB/km), respectively.

In each experiment, the nodes are initially placed randomly (used `UniformVariable` in NS-3) inside the mentioned simulation region boundary. After the start of the simulation, the nodes move according to the effect of ocean current, and follows the Meandering Current Mobility model [42]. The AUV, on the other hand, move with constant velocity and maintain the trajectory using its own navigation system. The node localization process is performed throughout the network. The criteria of any unlocalized node to get localized is reception of $n_{ref}|_{max}$ number of beacons from the AUV or beacon provider only. We apply the trilateration method for node localization, and thus, we consider $n_{ref}|_{max} = 3$, as the nodes have the knowledge of their z-coordinate. It may be noted further that the initial simulation boundary does not limit the node movement and thus, the boundary value does not have any effect on the localization process.

B. Performance Metrics

The proposed scheme was evaluated using the following performance metrics:

(i.) *Localization coverage:* This metric is defined as the ratio of the number of localized nodes to the total number of nodes in the network.

TABLE II: Simulation Parameters

Parameter	Value
Transmission Range of nodes (r)	1000 m
Transmission Range of AUV (R_a)	1000-2000 m
Node mobility model	Meandering Current Mobility model [42]
Node mobility (v_m)	0.5-2 m/s
Channel frequency	22 KHz
Modulation technique	FSK
Data rate	500 bps
Speed of sound	1500 m/s
Wave propagation model	Thorp's propagation model [40] Deep sea propagation model [41]
Transmission power	0.203 $watts$ [43]
Receive & Idle power	0.024 $watts$ [43]
Sleep power	3×10^{-6} $watts$ [43]
Initial energy of a node	150 J
Threshold battery level (W_{th})	50 J
Initial energy of the AUV	1000 J

(ii.) *Average energy consumption per localized node:* This value is computed as the ratio of the total energy consumption to the number of localized nodes. Average energy consumption per node is calculated as, $\mathcal{E}_{avg} = \frac{1}{n}\sum_{i=1}^{n}\mathcal{E}_i$.

(iii.) *Average localization error:* Average localization error is calculated using the following formula: $\epsilon = \frac{1}{n}\sum_{i=1}^{n}\sqrt{(x_i - x_i')^2 + (y_i - y_i')^2 + (z_i - z_i')^2}$, where, for any node i, (x_i,y_i,z_i) and (x_i',y_i',z_i') denote the estimated, and the original locations, respectively.

(iv.) *Average localization delay:* It is measured as the average time to localize a node after it receives the 'Wakeup' message.

C. Benchmark

We evaluate the performance of SEAL by comparing it with five existing schemes, namely, *Dive' n' Rise Localization* (*DNRL*) [24], *Three Dimensional Localization Algorithm for Underwater Acoustic Sensor Networks* (*3DUL*) [21], *Multi-stage AUV-aided localization* (*MSAL*) [27], *High-Speed AUV-Based Silent Localization* (*HASL*) [28], and the *Mobile AUV-aided Localization Scheme* (*MobiL-AUV*) [35]. DNRL, MSAL, HASL and MobiL-AUV are all mobile-anchor initiated node localization schemes. DNRL uses DNR-beacons, which act along the column of the 3D UWSN. On the other hand, in MSAL, the AUV moves along a fixed trajectory, by following a sinusoidal path throughout the network. The sensor nodes 'silently' receive beacon messages and localize themselves in DNRL. However, in MSAL, the AUV localizes the sensor nodes in the first stage, and the remaining nodes are localized using the nodes already localized in the first stage. 3DUL is an anchor-based scheme, where localization information iteratively propagates from the surface anchors. HASL is MobiL-AUV are both AUV-based silent localization schemes. In HASL, the beacon messages are provided by three AUVs, and the nodes localizes themselves by silently listens to the beacon messages. In MobiL-AUV scheme, the AUV aids the node localization process by providing beacons, whereas, the unlocalized nodes use spatial correlation to predict their mobility.

The transmission range of the DNR beacons (in DNRL), the sensor nodes (in 3DUL), and the AUV (in MSAL, HASL and MobiL-AUV) was set to 1000 m for all of the schemes during the simulations. In the simulation of DNRL, the DNR beacons were randomly deployed throughout the simulation region, and they broadcasted their coordinates periodically while moving along the ocean column. We also assumed that the DNR beacons drifted horizontally from their trajectory with the effect of underwater currents. The velocity of the AUV in all AUV-based schemes are set to 5 m/s, and the DNR-velocity, being comparatively slower, was set to 2.5 m/s.

TABLE III: Inter-node distance

No. of Nodes	Avg. Node Degree	Inter-node Distance		
		Avg.	Min.	Max.
10	1.33	213.89	451.47	2975.68
20	3.06	93.38	254.95	3275.97
30	4.64	61.61	196.22	3382.50
40	6.28	44.05	159.27	3466.53
50	8.06	36.10	127.44	3528.41

Justification for the Selection of Transmission Range: In Table III, we show the initial inter-node distance for 10-50 nodes deployed in a 2500 $m\times$ 2500 $m\times$ 2500 m region. Statistically, we plot the results with 95% confidence. It is evident from Table III, the inter-node distance decreases marginally with the increase in node density. Therefore, our selection of choosing the transmission range $R_i = [1000\ m, 1500\ m, 2000\ m]$ is motivated based such node distribution.

Additionally, long range underwater acoustic modems are available commercially (Teledyne modems 865-A and ATM-886 can have maximum transmission range of 10 km (http://www.teledynemarine.com/flash/index.html).

D. Results and Discussion

1) Localization coverage: The results for localization coverage for the proposed and benchmark schemes are shown in Figure 4. The localization coverage achieved using SEAL is nearly 52.18% and 44.32% higher than that achieved using 3DUL and DNRL. The localization coverage attained using MSAL is greater than that using 3DUL, or DNRL. Compared to MSAL, SEAL achieves nearly 13.72% increased localization coverage, on an average. This is due to the fact that MSAL has two stages of localization procedure. In the first stage, the nodes are localized with the help of the AUV, and in the second, the AUV-localized nodes act as reference nodes to localize the rest of the nodes. In the simulations, the second stage is executed multiple times before the simulation reaches the stop time of 600 s. Thus, the overall number of localized nodes is higher in MSAL, compared to 3DUL and DNRL. The deployment context-aware transmission range selection of the AUV results in achieving higher localization coverage in the proposed scheme. In other two benchmark schemes, HASL and MobiL-AUV, the localization coverage is 25.80% and 13.82% lower compared to SEAL. Both these schemes employ three AUVs as the location beacon provider to the unlocalized nodes. However, due to sparse nature of deployment, these schemes achieve less localization coverage compared to our proposed scheme, which leverages the intelligent selection of the transmission range to adapt in sparse UWSN scenarios. The localization coverage profile for all the schemes show similar properties — the number of localized nodes increases with the increase in the number of deployed nodes. The increasing trend is comparatively better in 3DUL scheme. This is due to the fact that with increase in the number of deployed nodes, the node density increases, which, in turn, increases the number of localized nodes. In the proposed scheme, the AUV intelligently adjusts the beacon transmission range according to the deployment scenario. Thereby, enhancing the localization coverage with trade-off in energy consumption.

We also calculate the localization coverage by varying the node mobility to 0.5, 1.0, and 2.0 m/s. The results of this experiment are show in Figure 5. For any mobility value, the localization success of the nodes exhibits a slow increasing pattern with higher node density in the network. However, with increased node mobility, the number of localized nodes reduces. In high node density scenarios, the variability in localization success is as low as 1-2%. However, the variability in localization coverage is nearly 6-10% in low node density of 10-20 nodes in the network. In the low density scenarios, the reduction of localization coverage is attributed with the dispersion of nodes due to the effect of passive node mobility. However, this effect is lower in case of higher node density scenarios. Thereby, the achieved localization coverage remains nearly similar with change in node mobility.

In Figure 6, we plot the results for localization coverage using the Deep Sea propagation model. In this case, the propagation loss increases, and consequently, the beacon transmission range affected. As a result, the overall localization coverage reduces for all the schemes. However, in SEAL, the AUV dynamically adjust the transmission range. Thereby, the enhanced localization coverage is achieved with trade-off in energy consumption of the AUV and the nodes.

2) Average energy consumption per localized node: The average energy consumption of the nodes during the localization process is shown in Figure 7. In this experiment, the node mobility was set to 0.5 m/s, and the number of nodes was varied between 10-50. We measure the average energy consumption for SEAL and the benchmark schemes. The results signify that SEAL maintains nearly 96.06% and 30.61% lower energy consumption than 3DUL and MSAL, respectively. However, DNRL results in 7.39% lower energy consumption than SEAL. In comparison to HASL and MobiL-AUV, the average energy consumption per node in SEAL remains 6.55% and 10.84% lower, respectively. Thus, DNRL is the most energy efficient among all the schemes considered. In our proposed scheme, the nodes participate in the process of creating the deployment context. As a result, the energy consumption of the nodes increases a bit compared to DNRL. The energy consumption of the mobile anchor-based schemes increases with the increase in the number of deployed nodes. For example, in SEAL, the increased node density of the network results in increased number of 'InfoAUV' message exchange between the AUV and the nodes. Consequently, the average energy consumption of the nodes increase. However, for 3DUL, the average energy consumption of the nodes decreases with the increase in

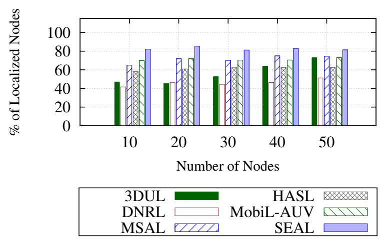

Fig. 4: Comparison of localization coverage ($v_m = 0.5\ m/s$, TP model).

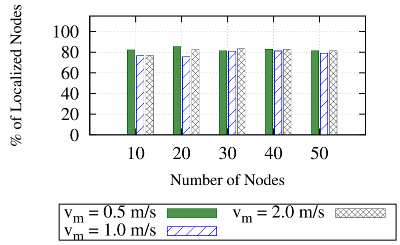

Fig. 5: Localization coverage using SEAL (TP model).

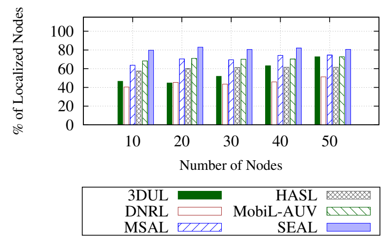

Fig. 6: Comparison of localization coverage ($v_m = 0.5\ m/s$, DSP model).

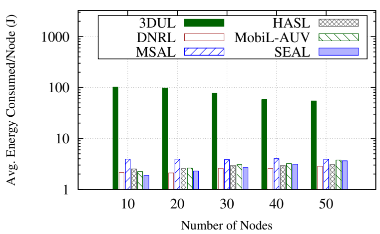

Fig. 7: Comparison of average energy consumption per localized node ($v_m = 0.5\ m/s$, TP model).

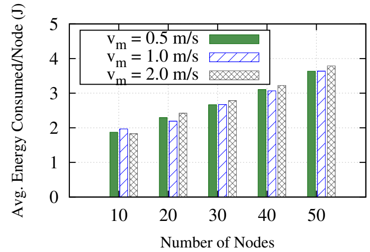

Fig. 8: Average energy consumption per localized node using SEAL (TP model).

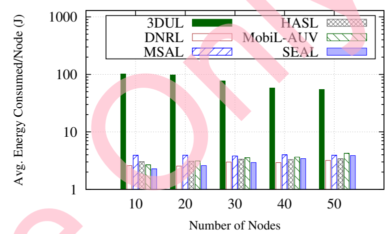

Fig. 9: Comparison of average energy consumption per localized node ($v_m = 0.5\ m/s$, DSP model).

node density. This is because of the iterative nature of the scheme. For higher node density, more number of nodes can be localized from similar number of messages. Thus, the average energy consumption per node is reduced. Compared to MSAL, the energy consumption of the deployed sensor nodes in SEAL is lower. In MSAL, the nodes localized by the AUV act as anchors for the remaining unlocalized nodes in the second stage of the scheme. Consequently, the average energy consumption of the deployed sensor nodes increase. In SEAL, the nodes mainly consume energy for 'Info and 'InfoAUV message exchange. During the localization process, the nodes listens to the location beacon transmitted by the AUV. Therefore, the energy consumption of the nodes remain low in this duration. Compared to HASL and MobiL-AUV, in the proposed scheme, the average energy consumption of the nodes remains lower due to the use of dynamic adjustment of the transmission range as per the deployment context. Also, due to the use of intelligent adjustment of transmission range, SEAL achieves increased localization coverage compared to most of the benchmark schemes.

In Figure 8, we show the results for the average energy consumption while varying the node mobility. In SEAL, the average energy consumption of the nodes increases with increase in the node density in the network. The energy consumption profile shows little variation over the change of node mobility. On an average, the change in energy consumption per node is nearly equal for the change of node mobility from 0.5 to 1.0 m/s. However, for the change of node mobility from 0.5 to 2.0 m/s, average energy consumption per node increases nearly 3.41%.

Figure 9, shows the results for average energy consumption of sensor nodes for using the Deep Sea propagation model. In this case, the acoustic signal incur higher transmission loss, and consequently, the average energy consumption of the nodes increase. A trade-off between energy consumption and transmission range exists here. For higher node density, the average energy consumption per node increases in SEAL, as the nodes exchange increased number of messages among themselves, on an average.

3) Energy consumption of the AUV: In Figure 10, we plot the results for the energy consumption of the mobile beacon node (e.g. AUV or the DNR-beacon) during the localization process for SEAL, MSAL, DNRL, HASL and MobiL-AUV (3DUL is not applicable to this comparison). In regard of the energy consumption of the mobile beacon, all the benchmark schemes result in increased energy consumption compared to SEAL. For MSAL, the energy consumption incurred by the AUV is nearly 54.43% higher than that incurred in SEAL. Also, for DNRL, the energy consumption is nearly 64.49% higher than SEAL. Whereas, in HASL and MobiL-AUV, it is nearly 68.04% higher than SEAL. In case of Deep Sea propagation model, in all the schemes, AUV's energy consumption increases and we observe similar pattern of results as in the Thorp's model.

The performance results indicate that the average energy consumption for both the nodes and the AUV is lower using SEAL compared to the benchmarks. On the other hand, in SEAL, AUVs energy consumption is adaptive to the deployment context — as the AUV intelligently selects the beacon transmission range based on the deployment context information from the sensor nodes. This essentially helps in achieving enhanced localization coverage while keeping the energy consumption of the AUV lower than the benchmark schemes.

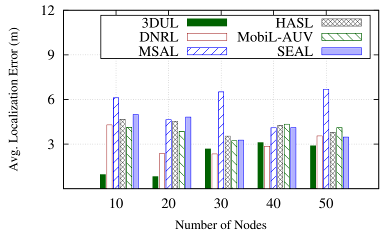

Fig. 11: Comparison of average localization error ($v_m = 0.5\ m/s$, TP model).

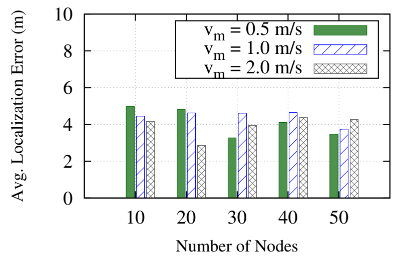

Fig. 12: Average localization error using SEAL (TP model).

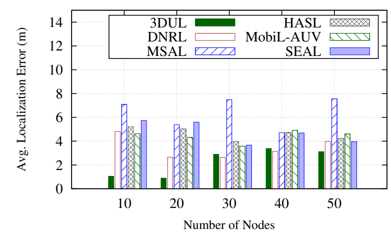

Fig. 13: Comparison of average localization error ($v_m = 0.5\ m/s$, DSP model).

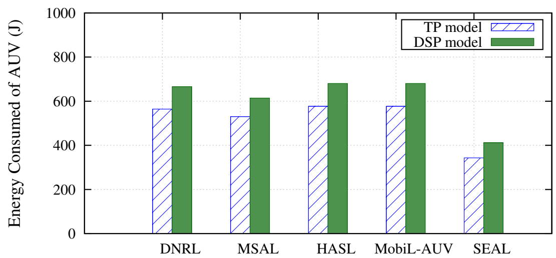

Fig. 10: Average energy consumption of the mobile-beacon (AUV or DNR), ($v_m = 0.5\ m/s$).

4) Average localization error: The simulation results for the metric localization error are shown in Figure 11. The results indicate that SEAL maintains 22.37% lower location estimation error than MSAL. Also, in both SEAL and MSAL, the error value shows less variability over the variation of the deployed number of nodes. The SEAL scheme maintain low estimation error than MSAL, as the localization process is of single stage, and nodes directly receive the coordinates from the AUV. Thus, the estimation error does not propagate throughout the network. Contrastingly, in MSAL, the localization process is of two stages — one is AUV aided and another is initiated by AUV-localized nodes of the first stage. However, another mobile anchor-based scheme, DNRL, shows fluctuation in localization error with the change of node density in the network. Mostly, the average localization error decreases with increased node density in the deployment. The localization error increases marginally with the increase in the number of nodes in the network for the 3DUL scheme. Compared to SEAL, the location estimation error is nearly 44.66% less in 3DUL. The reason behind this behavior is attributed to the type of localization scheme used in 3DUL. Due to the iterative approach, the sensor nodes near to the surface anchor are localized first. Following this, the neighbor nodes of the first-time localized nodes are localized, and consequently, the scheme is executed throughout the network. Thus, with higher node density, the location estimation error is higher in case of 3DUL. On the other hand, in SEAL, increased node density in the deployment decreases the average localization error. With increased node density, the probability of any unlocalized node forming robust virtual anchors plane with the AUVs beacon transmission position is higher. As a result, the average localization error decreases in SEAL. However, compared to DNRL, the average localization error in SEAL is higher. We explain such behavior with the robust virtual anchors plane. In DNRL, the nodes are localized by beacon messages from multiple DNR-beacons. The probability of forming a robust virtual anchors plane, with DNR-beacon location at different depth and different ocean column, is higher. Thus, DNRL achieve lower average localization error. However, with the increase in the node density, the average probability forming such plane decreases. As a result, the average localization error in DNRL increases in case of higher node density deployments. Therefore, there exists a trade-off between average localization error and beacon provider's (AUV or DNR) location. Similarly, the average localization error in HASL is 1.62% higher than SEAL, and in MobiL-AUV, it is 2.93% lower than SEAL. In both of these schemes, multiple AUVs are used as location beacon provider. Thus, the deployed nodes receive multiple location beacons from different anchor points, and the probability of forming a robust virtual anchors plane is higher compared to the proposed scheme.

In Figure 12, we plot the localization error by varying node mobility over various node density deployments. The location estimation error varies marginally with the increase in the number of deployed nodes. With increase in node mobility from 0.5 m/s to 1.0 and 2.0 m/s, the estimation error increases 6.8% and decreases 5.16%, respectively. In higher node mobility scenarios, the nodes disperse from its original position rapidly. As a result, the average localization error also changes rapidly.

We show the average localization error for using Deep Sea propagation model in Figure 13. In all the schemes, the localization error increases marginally. On average, the localization error in 3DUL and DNRL is 47.12% and 25.85% lower than SEAL. However, the average localization error is 43.12% higher in MSAL than that of in SEAL. The average localization error in HASL and MobiL-AUV is 0.60% and 4.69% lower than SEAL, respectively. The effect of node density on localization error is also similar as with the Thorps propagation model.

5) Average localization delay: The average localization delay for the nodes for SEAL and it benchmark schemes are plotted in Figure 14. The results show that the average localization delay using the SEAL and MSAL schemes does not depend on node density factor. For this metric, SEAL and MSAL results in nearly similar performance. Compared

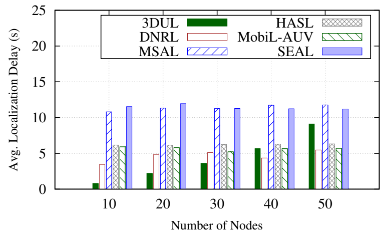

Fig. 14: Comparison of average localization delay ($v_m = 0.5\ m/s$, TP model).

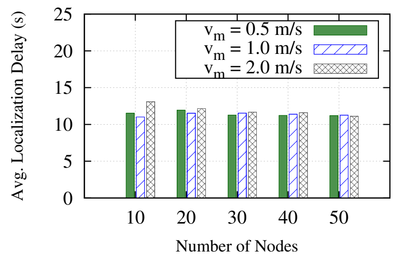

Fig. 15: Average localization delay using SEAL (TP model).

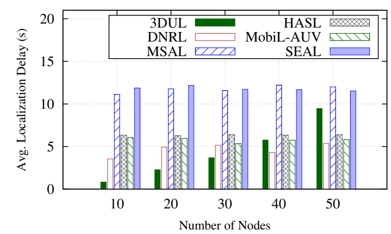

Fig. 16: Comparison of average localization delay ($v_m = 0.5\ m/s$, DSP model).

to SEAL, the localization delay is 59.31% less in DNRL. In DNRL, a node localizes itself after receiving location beacons from multiple DNR beacon nodes. Alternatively, in SEAL, only one AUV is responsible for the broadcast of location beacons. This way, the localization delay increases in using the SEAL scheme. Compared to SEAL, on an average, the localization delay is 62.1% lesser using the 3DUL scheme. In 3DUL, with increase in the node density, the delay increases gradually with the increase in the number of localization iterations. In low density networks, delay is much lower using 3DUL than using SEAL, and in high density networks, it is nearly 18.64% lower using 3DUL. In higher node density, due to the adaptive transmission range selection of the AUV, the nodes receive the required number of beacons quickly. As a result, the overall localization delay decreases in SEAL with increase in node density. The average localization delay achieved in HASL and MobiL-AUV are respectively 45.43% and 50.55% less compared to SEAL. This is due to the fact that in both these schemes location beacon is provided by three AUVs and thus, on an average the location beacon interval is less. As a result, the localization delay remains lower compared to the proposed scheme.

We show the results for localization delay with different node mobility in Figure 15. With increase in the node mobility value, the variation of localization delay shows an decreasing trend. Overall, the localization delay exhibits little variability with node density when the node mobility value is set to 0.5 and 1.0 m/s. However, in case of node mobility set to 2.0 m/s, the results indicate a decreasing trend with increased node density of the deployment.

In low node density deployments, the effect of node dispersion with passive mobility increases the time between the reception of beacons, on an average. Thereby, increasing the average localization delay with increase in node mobility. However, such effect is lower in case of higher node density. Consequently, the average localization delay has marginal change with increase in node mobility.

In Figure 16, we plot the results for the average localization delay in case of Deep Sea propagation model. In this scenario, the effect of node density is similar to that of in Thorps propagation model. However, the average localization delay increases marginally for the change of propagation model.

6) Discussions: From the results, it is evident that the proposed scheme, SEAL, is able to achieve greater localization coverage compared to the benchmark schemes. The trade-off for this localization success is in terms of increased energy consumption of the deployed nodes, especially compared to DNRL scheme. Typically, in mobile beacon-based schemes such as DNRL, HASL and MobiL-AUV, the nodes passively listen to the location beacon message. Therefore, the energy consumption of these nodes remain significantly low. Compared to the proposed scheme, the energy consumption of the nodes in DNRL is less. However, in case HASL and MobiL-AUV, the average energy consumption of the nodes increases as they receive more number of beacons from multiple AUVs. Although, compared to DNRL, MSAL, HASL and MobiL-AUV, the proposed scheme achieves significant improvement in case of maintaining the energy-efficiency of the mobile beacon provider. In the proposed scheme, the nodes help in collecting the deployment context information using the NIDL algorithm, and then, using the STARS algorithm, the AUV is enabled to dynamically select a transmission range based on the context information. This intelligent selection of transmission range helps in minimizing the energy consumption of the AUV while the process of context information collection results in increased energy consumption for the deployed nodes.

VI. Conclusion

In this paper, we proposed a localization scheme, named as Self-adaptive AUV-based Localization (SEAL), for use specifically in sparsely deployed UWSNs. The sparse nature of deployment in UWSN is cost-effective. However, it results in low localization success when the existing node localization schemes are applied. The proposed scheme uses an AUV, instead of surface-based anchors, as the beacon message provider. We propose a *self-adaptive* transmission range selection scheme, which empowers the AUV to intelligently adjust the transmission range in a sparse deployment scenario. Thus, in the proposed scheme, the AUV is able to decide deployment-aware transmission range. Overall, the localization coverage of the network increases up to 80% compared to the DNRL scheme, and nearly 52%, 16%, 35% and 16% high compared to the 3DUL, MSAL, HASL and MobiL-AUV schemes, respectively. At the same time, the proposed scheme maintains lower energy consumption of the sensor nodes (expect compared to DNRL) as well as the AUV compared to the benchmark schemes.

The AUV-based schemes are successful in upward refracting underwater environments. However, UWSNs face various environmental challenges such as jamming, interference, and variable sound speed. In the future extension of this work, the proposed scheme may be re-designed to operate under such challenging environments. The trajectory of the AUV is another important factor in determining the localization success of the deployed nodes. Thereby, we plan to evaluate the proposed scheme for various AUV trajectories in the future.

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