Experiments with aLS-Coop-Loc cooperative combined localization and time-synchronization

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Abstract—**Performing real world experiments with underwater communication is difficult and time-consuming. Input for evaluation of localization and time-synchronization derived from experiments is not readily available.**

Using real-world experiments we evaluate the performance of our cooperative combined localization and time-synchronization approach called aLS-Coop-Loc and a non-cooperative approach. We perform experiments using the SeaSTAR Proteus node and a Commercial Off-the-Shelf (COTS) node from Kongsberg Maritime at a lake and at Strindfjorden in Norway. These experiments provide realistic insight into ranging performance in real-world environments.

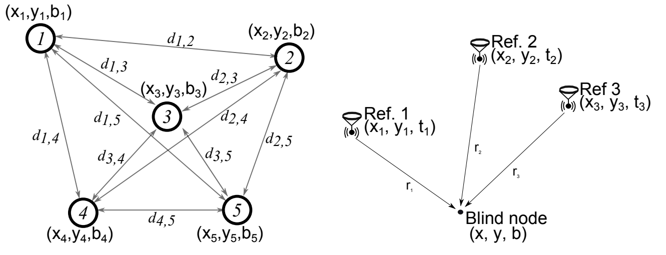
Evaluation shows that the cooperative approach outperforms non-cooperative approaches in terms of accuracy of localization and time-synchronization. aLS-Coop-Loc provides about about 2% to 34% better position accuracy and 50% improved time-synchronization.

I. INTRODUCTION

In underwater research, work has been mostly limited to simulation. Performing real world experiments with underwater communication is difficult and time-consuming. Therefore researchers in the field of underwater communication mostly tend to limit themselves to simulations or theoretical work only. Input for such simulations, derived from experimental work, is not readily available. We perform experiments using the SeaSTAR Proteus node and an COTS node from Kongsberg Maritime called cNODE Mini [4].

Localization and time-synchronization are import aspects in Underwater Acoustic Sensor Networkss (UASNs). When performing localization and time-synchronization, it is beneficial to perform localization and time-synchronization simultaneously. This allows usage of one-way ranging and reduces the communication overhead and improves accuracy. Combined one-way ranging localization and time-synchronization exist for both cooperative [8] as well as non-cooperative [5] approaches.

In [8] we have introduced a cooperative approach to localization and time-synchronization called aLS-Coop-Loc. Using simulation we have shown [8] that a cooperative combined localization and time-synchronization approach has improved accuracy compared to non-cooperative localization.



(a) Cooperative (b) Non-cooperative

Fig. 1. Example of cooperative and non-cooperative localization. Cooperative localization uses all pair-wise measurements available, while non-cooperative localization has only measurements between reference nodes and blind-nodes.

In this paper we evaluate the performance of both aLS-Coop-Loc as well as non-cooperative one-way ranging combined localization and time-synchronization. Moreover, our real world experiments provide insight into the performance of underwater acoustic ranging in a realistic environment. The short-range experiment shows significant ranging errors, Section III-D we identify possible sources of these errors.

For our applications we are interested in short-range networks deployed in shallow water in a 2d setup with all nodes deployed at the same depth. We therefore evaluate the short-range ranging performance in real world experiments and use the derived error distribution in simulation of 2d networks to evaluate the short-range performance in different setups with different number of nodes. Moreover we perform tests with long-range setups and show this setup has much better ranging performance compared to short-range ranging.

This paper is organized as follows: In Section II we discuss related work on combined localization and time-synchronization. Real-world experiments are described in Section III, including the experiment setup and results. Section III-D discusses the possible sources of errors for the significant ranging errors in the short-range measurement setup. In Section IV we conclude this paper.

II. RELATED WORK

In this section we review time-synchronization and combined localization and time-synchronization for both non-cooperative and cooperative networks.

A. Time-Synchronization

Time-synchronization is the process of synchronization of the clocks at different nodes such that an agreement is reached on what the current time is. This notion of ‘time‘ does not necessarily have to be global (world time), as the nodes can agree on a local time for the complete network.

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Let us consider a network of N nodes. Every node has a clock and all nodes are assumed to have the same frequency increment. The clock is modeled as a $\mathbb{R}$ variable, which increases continuously over time. We denote the clock of node i as ϕ_i. Every clock has a bias, this is an offset of the clock compared to another clock. We denote the bias of the clock as b_i. To synchronize a network of N nodes all biases of all the clocks should be calculated according to:

$$\phi_1 - b_1 = \phi_2 - b_2 = \cdots = \phi_N - b_N \tag{1}$$

During the measurement of a single propagation delay clock-drift occurs. Considering that we uses ranges up to 1500 meters, and use two-way ranging, the measurement time of a single measurement is up to:

$$\frac{2 \times 1500m}{1500\frac{m}{s}} = 2s \tag{2}$$

We use a crystal having an accuracy of better than 50ppm, yielding a clock drift during the ranging measurement of:

$$2s \times 50 \times 10^{-6} = 100 \times 10^{-6}s \tag{3}$$

In meters this yields an error of:

$$100 \times 10^{-6}s \times 1500\frac{m}{s} = 0.15m \tag{4}$$

Hence, we consider the impact of the clock drift during the ranging measurement not significant.

B. Non-cooperative Localization and Time-Synchronization

A number of non-cooperative combined localization and time-synchronization already exist, an example of which is the Global Positioning System (GPS) [5]. In [7] a combined communication scheduling with a least-squares solution to localization and time-synchronization is presented to provide a localization and time-synchronization system.

Figure 1(b) shows a non-cooperative localization and time-synchronization setup. All reference nodes have a known position (x_i, y_i) and are assumed to be synchronized, i.e. their clock biases are known. The reference nodes send out their position information (x_i, y_i) and the time when a message was sent (t_i). A blind node records the arrival time of the message (r_i) and is able to calculate the Time-of-Flight (TOF) of the message with a clock-bias of its local clock (b). The blind-node should estimate both its position (x, y) and clock-bias (b). This is done by minimizing the following cost function:

$$\min_{x,y,b} \sum_{i=1}^{N} (\sqrt{(x-x_i)^2 + (y-y_i)^2} - v \cdot (r_i - t_i - b))^2, \tag{5}$$

where v is the propagation speed of the signal, which is commonly approximated to $1500m/s$ in water.

C. Cooperative localization and time-synchronization

Multi-Dimensional Scaling (MDS) [2] is a well known approach which has been applied to underwater cooperative localization before [3]. MDS, however, provides only localization. aLS-Coop-Loc [8] provides a combined localization and time-synchronization approach for cooperative networks. A combined localization and time-synchronization has been shown to have significant benefits in terms of communication overhead as well a localization and time-synchronization accuracy.

aLS-Coop-Loc follows a similar approach as MDS, however, rather than just calculating the position (x, y) of nodes, also the unknown clock bias (b) is calculated. Let us consider nodes are positioned in a D dimensional space, where D = 2 or 3. Let $\vec{x}_{i=1\ldots N}$, $x_i \in \mathbb{R}^D$ be the vector or coordinates of node i and assume $b_i \in \mathbb{R}$ is the clock bias of node i. Let us consider two nodes with indices i and j out of a network of N nodes. If we define the transmission time of a message on node i as t_i and the reception time of the message as r_i and also consider the clock bias of both nodes b_i and b_j, we can measure the TOF between two nodes as follows:

$$(r_i - b_i) - (t_j - b_j) = tof_{i,j} \tag{6}$$

From the tof we can calculate the pseudo-distance between the two nodes (τ) by using the propagation speed $v \approx 1500$ m/s. The measured pseudo-distance between nodes (denoted by $\tau_{i,j}$), measured during the operation of an underwater network, and the estimated distance between the nodes, calculated during the process of iterative optimization, should converge to the same value:

$$\tau_{i,j} = v((r_i - b_i) - (t_j - b_j)) \rightarrow ||\vec{x}_i - \vec{x}_j|| - v(b_i - b_j) \tag{7}$$

We measure these pseudo distances $(\tau_{i,j})$ between nodes using acoustic communication during the operation of the network and place them in a dissimilarity matrix:

$$\tau = \begin{pmatrix} \tau_{1,2} & \tau_{1,3} & \tau_{1,4} & \cdots & \tau_{1,N} \\ & \tau_{2,3} & \tau_{2,4} & \cdots & \tau_{2,N} \\ & & \tau_{3,4} & \cdots & \tau_{3,N} \\ & & & \cdots & \cdots \\ & & & & \tau_{N-1,N} \end{pmatrix}$$

Rather than measuring the actual distance between the two nodes, we measure the distance between nodes with a clock bias error of the sender and a clock bias error of the receiver. After measuring the propagation delay between the nodes with the unknown clock biases, for every we estimate the position $(\vec{x}_i \in \mathbb{R}^D)$ and clock-bias $(b_i \in \mathbb{R})$ by minimizing the following cost function:

$$cost = \min_{x_1 \ldots x_N, b_1 \ldots b_N} \sum_{i=1}^{N} \sum_{j=i+1}^{N} (\tau_{i,j} - ||\vec{x}_i - \vec{x}_j|| - v(b_i - b_j))^2 \tag{8}$$

Note that the upper triangle of the dissimilarity matrix is used, hence the approach uses one-way ranging.

III. REAL WORLD EXPERIMENTS

To better evaluate performance of cooperative and non-cooperative localization approaches in more realistic environments, we perform ranging measurements in three different underwater environments as described below. These experiments were performed using two underwater node platforms, i.e., (i) the SeaSTAR Proteus node and (ii) commercially available Mini node of Kongsberg Maritimes.

The SeaSTAR Proteus node is an underwater node developed within the SeaSTAR project [1] as an inexpensive open platform for underwater communication experiments. The node is based on an off-the-shelf ARM Cortex-M3 which was extended by a custom analog acoustic transceiver front-end and a HopeRF RFM22B 433 MHz RF wireless link module. This node communicates in the acoustic frequency range of 20khz-30khz and has a bitrate of 100 baud. A three-cell 2200 mAh LiPo battery was used to power each node. The radio module is used to provide a connection to the shore when the node is deployed at the surface, allowing for an easy to use high bandwidth connection to gather experimental data. The radio connection is used to both collect the measurement data as well as to time-synchronize the nodes. The Kongsberg does not have this radio interfaces and uses two-way ranging and uses the acoustic link to gather the measurement data. Using this hardware we have performed three different test:

- **het Rutbeek short-range**: 6 SeaSTAR Proteus nodes were deployed in a recreational lake in city of Enschede. Distances between the nodes were small, ranging between 12 and 55 meters. Two different deployments were tested, one of which is shown in Google Earth as illustrated in Figure 2. The only difference between the first and the second setup are the shifted position of the deployed nodes. The nodes are deployed at the surface allowing the antenna to have a radio connection with the shore, data was collected and nodes were time-synchronized using this radio connection . At the shore a laptop was collecting all data from all nodes to log files. Using sandbags and ropes the nodes were fixed to the lake bottom.
- **Strindfjorden short-range**: In this short-range setting, nodes were deployed from a pier close to the shore of Strindfjorden in Trondheim Norway. Distances between the nodes were small, ranging between 7 and 25 meters. This test was performed using both the SeaSTAR Proteus node and the commercial Mini nodes of Kongsberg Maritimes.
- **Strindfjorden long-range**: In the long-range setup, nodes were deployed from a research vessel and were fully submerged all at the same depth of about 200 meter and with distances between nodes ranging from 200 meters up to 1.5 kilometers. This test was performed using the commercial Mini nodes of Kongsberg Maritimes. Ranging measurements were performed using two-way ranging and data was collected using an acoustic data link.

The parameters of the different setups are summarized in Figure 3. In the above described setups we first measure the position of the nodes using a GPS receiver. We then determined the distance between the nodes using acoustic ranging. We compare the acoustic ranging results with the distances calculated based on the GPS positions. The error of the GPS distance compared to the acoustic ranging is expressed as a percentage of the range. From these errors, we calculate the normal distribution of the links denoted by $\mathcal{N}(\mu, \sigma)$.

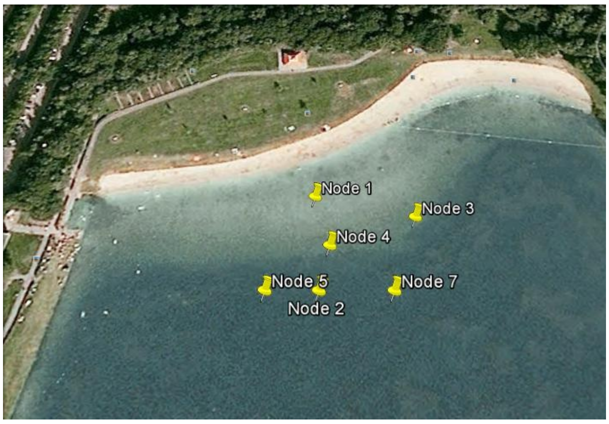

Fig. 2. Example of network deployment on Google Earth, nodes were deployed up to a distance of 50 meters from each other.

Setup	Hardware	#Nodes	Distances	Depth
Rutbeek short-range 1	SeaSTAR	6	12-55m	Surface
Rutbeek short-range 2	SeaSTAR	6	12-55m	Surface
Strindfjorden short-range	SeaSTAR	6	7-25m	Surface
Strindfjorden short-range	Kongsberg	4	7-25m	Surface
Strindfjorden long-range	Kongsberg	5	0.2-1.5km	200m

Fig. 3. Parameters of the different setups, all the nodes are deployed at the same depth and a 2d setup is formed.

A. *het Rutbeek short-range*

Using the experimental setup we determine the ranging performance of the SeaSTAR Proteus node in short-range setups. The ranging results from the different experiments vary from reasonably accurate (error of about 10%) to very inaccurate (error up to 100% of the range). Using the measurements we were able to derive ranging error distributions.

The average distributions for the Rutbeek setups are:

$$\mathcal{N}(11.53, 16.48), \mathcal{N}(27.85, 42.22)$$

The results of the ranging show a significant ranging error. In Section III-D we further discuss what sources of error we have identified in the test, in future work we would like to improve the setup and reduce the ranging errors.

Using the ranging error distributions derived from the experiments, we make an estimation of the performance of the localization and time-synchronization approaches in such an environment. For every error distribution we run a simulation, generating link range estimations using the error distributions derived from the experiments. This simulates an environment which is similar to the environment in which we performed the experiment, yet allows us to vary other settings such as number of reference nodes and total number of nodes in the network.

Method	Position error	Time error
Non-Cooperative	11.8 m (1.00)	4.7 msec (1.00)
aLS-Coop-Loc (5)	8.2 m (0.69)	2.2 msec (0.47)
aLS-Coop-Loc (4)	9.8 m (0.83)	2.5 msec (0.53)

(a) Rutbeek deployment 1 $\mathcal{N}(11.53, 16.48)$

Method	Position error	Time error
Non-Cooperative	26.3 m (1.00)	16.4 msec (1.00)
aLS-Coop-Loc (5)	24.2 m (0.92)	6.4 msec (0.39)
aLS-Coop-Loc (4)	25.4 m (0.97)	6.2 msec (0.38)

(b) Rutbeek deployment 2 $\mathcal{N}(27.85, 42.22)$

Fig. 4. Results performance evaluation with 16 nodes, table shows the positioning error, time-synchronization error for different localization approaches run with different error parameters obtained from real measurements performed in Rutbeek. Results between brackets are the results relative to the non-cooperative approach.

The evaluation was performed for a network of 16 nodes, with 5 reference nodes for the non-cooperative localization and 4 and 5 reference nodes for cooperative localization, with nodes randomly positioned on an area of 50x50m. The calculated positions are limited to the bounding box of the localization area and the position of the reference nodes are at the corners of the localization area. The results of this evaluation is shown in Figure 4.

From the results illustrated in Figure 4 it can be seen that cooperative localization using 4 reference nodes outperforms non-cooperative localization: position accuracy is 31% and 8% more accurate and time-synchronization is about 53% and 61% more accurate. In the case of having 4 reference nodes, cooperative localization is still able to calculate the position and perform time-synchronization, and does so with a slightly improved accuracy in terms of position and a much better time-synchronization accuracy compared to non-cooperative localization.

We have also evaluated the performance of the localization algorithm with different number of nodes in the network. Results are shown in Figure 5 and Figure 6. The aLS-Coop-Loc approach was evaluated for networks with 4 and 5 reference nodes. What can be seen from the results is that the non-cooperative performance is independent of the number of nodes in the network. The aLS-Coop-Loc results are dependent on the number of nodes in the network. The aLS-Coop-Loc(5) approach outperforms the non-cooperative localization on average approach by 2% to 27% for position accuracy and about 50% for time-synchronization.

From the results it also becomes clear that using fewer reference nodes (4 in this case) for aLS-Coop-Loc has in some cases worse performance than non-cooperative localization. The average position accuracy for aLS-Coop-Loc(4) ranges from 17% worse to 19% improved performance. From these results it also can be seen that the number of nodes has an effect on the performance for cooperative localization and time-synchronization.

B. Strindfjorden short-range setup

In the Strindfjorden short-range setup we have performed a ranging performance test using both the Kongsberg Mini and

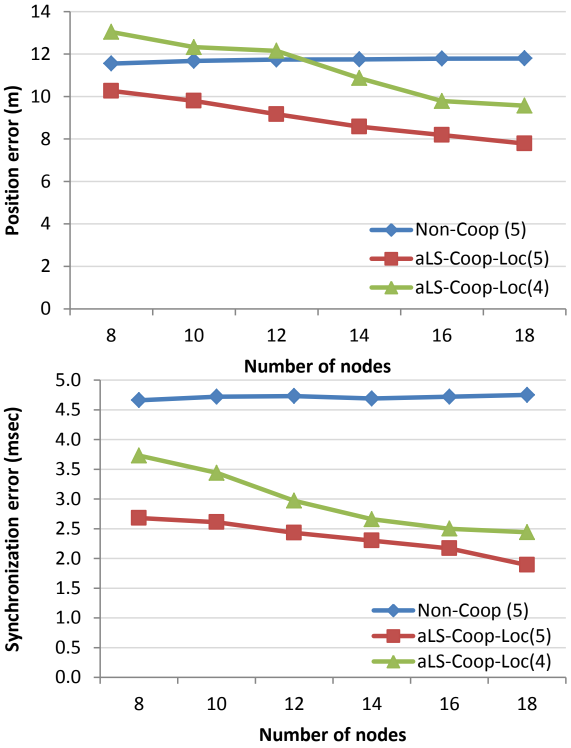

Fig. 5. Performance results using the parameters obtained in Rutbeek deployment 1, run with increasing number of nodes in the network.

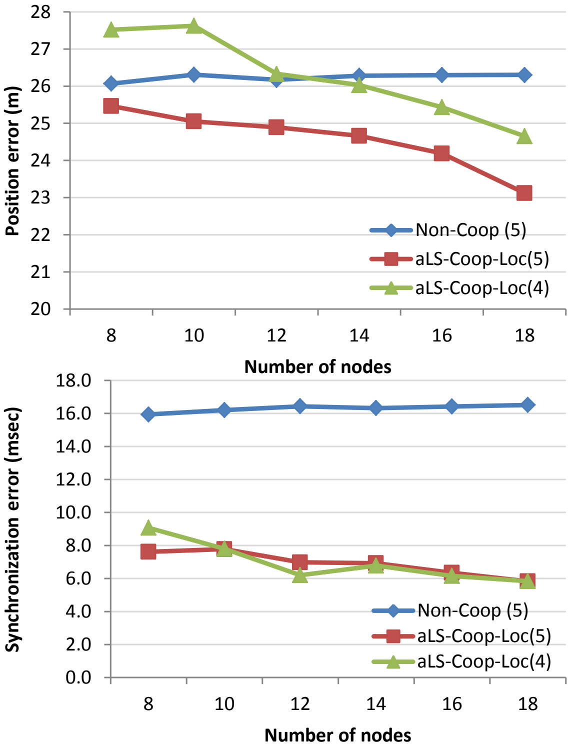

Fig. 6. Performance results using the parameters obtained in Rutbeek deployment 2, run with increasing number of nodes in the network.

Link	**Distance**	μ	σ
Node 2 - 3	6.94 m	-21.54	6.97
Node 2 - 4	7.46 m	-29.11	4.23
Node 2 - 5	18.03 m	13.46	1.07
Node 3 - 4	6.79 m	-34.88	1.91
Node 3 - 5	11.09 m	-10.99	3.02
Node 4 - 5	15.19 m	-7.61	2.43
Overall		-15.18	16.05

Fig. 7. Results ranging short-range experiments performed using the Kongsberg Mini. Ranges were derived from the measured positions using GPS. Errors are shown as percentage of the range.

Method	Position error	Time error
Non-Cooperative	15.0 m (1.00)	7.3 msec (1.00)
aLS-Coop-Loc (5)	11.5 m (0.77)	3.3 msec (0.45)
aLS-Coop-Loc (4)	13.9 m (0.93)	3.4 msec (0.47)

(a) SeaSTAR proteus $\mathcal{N}(18.65, 20.92)$

Method	Position error	Time error
Non-Cooperative	10.8 m (1.00)	3.9 msec (1.00)
aLS-Coop-Loc (5)	7.0 m (1.03)	1.7 msec (0.59)
aLS-Coop-Loc (4)	8.1 m (0.77)	2.1 msec (0.57)

(b) Kongsberg Mini $\mathcal{N}(-15.18, 16.05)$

Fig. 8. Performance result with the parameters derived from the Strindfjorden short-range test setup.

the SeaSTAR Proteus node in the same near-shore short-range setup. For the near-shore experiments, again, a GPS receiver was used.

For the SeaSTAR nodes the average ranging error distribution is:

$$\mathcal{N}(18.65, 20.92)$$

The error distribution for the Kongsberg Mini nodes is:

$$\mathcal{N}(-15.18, 16.05)$$

Both the SeaSTAR Proteus as well as the Kongsberg Mini nodes show significant range errors in this short-range setup, in the next section we evaluate a long-range setup and we will see that these large errors are not present in a long-range setup.

The results of the individual link ranging errors using the Kongsberg Mini are shown in Figure 7. Interesting is that the μ of the ranging error is for most links negative. This indicates that there may be a systematic error in the ranging system. When performing a range measurement, the nodes compensate for the processing delay of a packet. We suspect that an error in the estimate of the processing delay causes the ranges to be underestimated.

Using the derived error distributions we have calculated the position accuracy of both the SeaSTAR Proteus as well as the Kongsberg Mini node in this environment. Results are shown in Figure 8. Again, the cooperative localization approach outperforms a non-cooperative localization approach.

C. Strindfjorden long-range

Tests were performed over longer ranges in an off-shore test in 200 meter deep water. The positions of the nodes underwater in the long-range test were determined using the Kongberg HiPAP system, a Super Short Base Line (SSBL) dynamic positioning system.

Link	**Distance**	μ	σ
Node 1 - 3	0.189 km	-3.09	5.50
Node 1 - 4	1.090 km	-2.18	0.51
Node 1 - 5	1.551 km	-2.23	0.45
Node 1 - 6	1.270 km	-1.48	0.44
Node 3 - 5	1.473 km	-1.42	0.30
Node 3 - 6	1.208 km	-1.41	0
Node 4 - 6	0.238 km	-8.86	0.32
Node 5 - 6	0.302 km	0.55	0.13
Overall		-3.12	3.60

Fig. 9. Results long-range ranging experiments performed using Kongsberg hardware. Ranges were derived from the measured positions using SSBL. Errors are shown as percentage of the range.

Method	Position error	Time error
Non-Cooperative	28.05 m (1.00)	8 msec (1.00)
aLS-Coop-Loc (5)	17,04 m (0,61)	4 msec (0.50)
aLS-Coop-Loc (4)	19,91 m (0.71)	5 msec (0.63)

Fig. 10. Performance result for the long-range experiments with the parameters derived using Kongsberg hardware, simulation was performed on an area of 500x500m.

Results for the experiments are shown in Figure 9. For every link where measurements were available the error between the pre-determined range and the acoustically measured range was determined. These errors were expressed as a percentage of the range. From these errors the normal distribution of the link error was determined, denoted by $\mathcal{N}(\mu, \sigma)$.

What can be seen from the results show in Figure 9 is that the ranging error of the long-range experiments were quite low. The results of the near-shore experiment show much greater errors than the short-range experiment. We suspect that in shallow water and short-range deployments it is much harder to perform accurate range measurements, due to strong multipath effect being present.

We have performed the performance evaluation again with the measured error distributions of this experiment:

$$\mathcal{N}(-3.12, 3.60)$$

The evaluation was performed for a network of 16 nodes, with 5 reference nodes for the non-cooperative localization and 4 and 5 reference nodes for aLS-Coop-Loc. Results are shown in Figure 10. This time, the deployment area of the nodes was changed to 500x500m. Again, results obtained from the long-range experiment using the Kongsberg Minis match the previous obtained results, i.e. cooperative localization and time-synchronization outperforms the non-cooperative approach for the same number of reference nodes.

D. Evaluation of ranging errors

The tests involving shallow water short-range ranging experiments show significant errors. To get a better estimation of where these errors come from, we identify the following possible source of these errors:

- **GPS and SSBL error**. The measurement of the positions using the GPS (and the SSBL) result in incorrect estimation of the actual ranges. The GPS receiver indicated a positioning error of 1-3 meter, this is however an absolute error. The relative positioning error appears to be much smaller when looking at the positions placed in Google Maps. In future work it would be better to use a more accurate GPS receiver and validate some of the ranges with a laser rangefinder.

- **Dynamics of the nodes**. During the Rutbeek experiment, the nodes were not fixed and were moving with the wind. This causes the nodes to deviate from the GPS measured positions. In the Strindfjorden experiment the nodes were deployed from a pier and the position of the nodes during the experiment was therefore much more stable. A fixed deployment of the nodes is therefore preferred, deploying the nodes close to the bottom may result in a more fixed placement of the node but the radio interface provided by the SeaSTAR node can then not be used.
- **Incorrect Time-of-Arrival (TOA) processing delay**. In software the modem needs to compensate for the processing delay of a packet to determine the accurate TOA. If this processing delay is incorrect or the processing delay is not constant, the TOA is incorrectly estimated. In the estimations performed with the Kongsberg Mini, the ranges are almost always underestimated. We suspect incorrect large processing delay results in the underestimation of the actual range.
- **TOA estimation error**. The last error we can identify is the TOA measurement performed by the node. In a highly reflective environment many multipath reflections are present and the strongest path is not always the direct path. If the modem decodes the strongest path, the measurement will contain an error. This effect has also been observed in by us in [6] and other authors:

  > The identification of the direct blast becomes virtually impossible under noise- and reverberation-limited conditions [3]

IV. CONCLUSION

Localization and time-synchronization are important aspects of underwater acoustic sensor networks, as they give meaning to sensor measurements by adding information on where and when measurements are taken. Localization and time-synchronization, however, are traditionally done separately. A combined localization and time-synchronization approach has significant benefits in communication overhead and localization accuracy. We have compared a non-cooperative and a cooperative combined sone-way ranging localization and time-synchronization approach called aLS-Coop-Loc.

We have performed real-world tests using the SeaSTAR Proteus node and with COTS underwater nodes from Kongsberg. These tests provide insight into the performance of underwater acoustic ranging in realistic environments. Tests were performed at a recreational lake near the campus of the university and in Strindfjorden near Trondheim. The measurements from the test were used to derive an error model for the acoustic ranging. Using this error model we evaluated the different localization approaches. The experimental results show aLS-Coop-Loc outperforms non-cooperative localization with improved position accuracy of about 8% to 31% when the same number of reference nodes are used.

We have performed evaluation of the different approaches with increasing number of nodes in the network. The performance of the non-cooperative approach is unaffected by the number of blind nodes in the network. The performance of cooperative localization improves with increasing number of nodes in the network in such environments and cooperative localization improves position accuracy up to 34% compared to non-cooperative localization.

The real-world experiments show significant ranging errors in the short-range scenario, we have identified a number of possible sources for these errors. Using the COTS nodes from Kongsberg Maritime we have performed a long-range experiment. For the long-range measurement, the relative ranging errors are considerably smaller than for short-range setups.

Our experiments in realistic environments provide insight into the performance of ranging in real-world environments. Using the derived ranging error models we have shown cooperative localization outperforms non-cooperative localization in terms of localization and time-synchronization accuracy. In the future we would like to improve the experiment setup and perform better quantification of the performance of ranging in realistic environments. We would like to investigate if these short-range environments are really noise- and reverberation-limited conditions.

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