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DESIGN METHOD FOR LONG-TERM EVALUATION OF UNDERWATER ACOUSTIC COMMUNICATIONS AND NETWORKS IN A NORWEGIAN FJORD ENVIRONMENT

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ABSTRACT

Fjords often have difficult underwater acoustic propagation properties, such as the acoustic shadow zones created by highly dynamic bathymetry and thermocline/halocline. In addition, shallow-water coastal underwater acoustic horizontal communications are characterized by several reflections at the boundaries creating complex and time-varying multipath channel structures. We present an iterative simulation and experiment-based method for designing and evaluating an underwater acoustic communication system and the network layers built on it. First, we present the sound speed profiles collected throughout the year in the fjord at Austevoll in western Norway. Then we discuss the setup used to collect acoustic channel impulse responses in the frequency band 55-65 kHz in the same geographical area. We then provide the results of numerical modeling for the acoustic propagation and present the methodology that we plan to implement in the next few years for a long-term evaluation and improvement of acoustic sensor networks in fjord environments.

Keywords: *Underwater communications in fjords, Underwater sensor networks, Acoustic propagation numerical modeling).*

1. INTRODUCTION

In this paper, we propose a method to test and validate underwater acoustic communication systems and network protocols, where data traffic specifications are driven by both coastal waters observation science and aquaculture water quality monitoring needs.

In the last twenty years, a vast literature has focused on underwater acoustic sensor networks and communication systems, but lately more and more solutions have focused on the adaptivity of the communication system and networking protocols based on the changing environment [1–4].

Although there are numerous commercially available underwater acoustic modems [5–11], more and more research groups are developing their own low-cost solutions, as discussed in [12]. The development of a low-cost underwater software-defined acoustic modem is also part of the Centre for Research-based Innovation SFI Smart Ocean [13].

This paper provides a description of the initial tests carried out to characterize the underwater acoustic channel over different frequency bands in October and November 2022 in the Austevoll area in western Norway. We also present the sound speed profiles derived from Conductivity, Temperature, and Depth (CTD) casts taken at each experimental campaign. We present the numerical propagation modeling for the specific environment over the communication channel between a submerged remote node and a modem placed on a dock. We also show the estimated channel impulse responses we collected over the 55-65 kHz band. We conclude by presenting the follow-up studies and experimental campaigns and how this is part of an iterative method for the evaluation and innovation in the field of underwater acoustic sensor networks for specific industrial and scientific applications and environments.

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2. EXPERIMENTAL FACILITY AND ENVIRONMENTAL CTD DATA

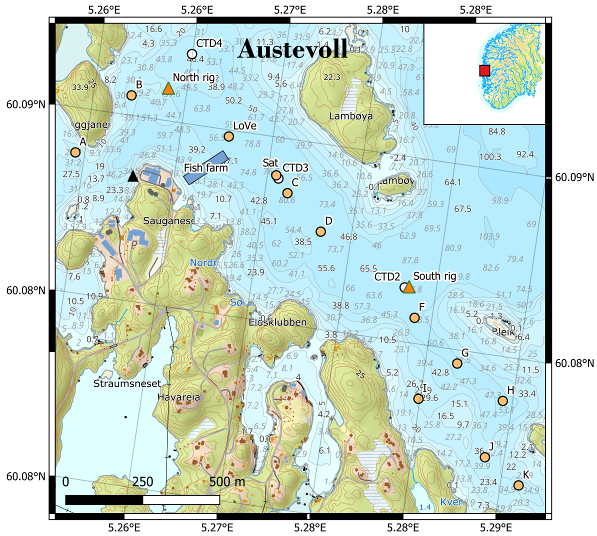


Figure 1: Experimental area and facility.

Fig. 1 shows the area at Austevoll in western Norway which is available for testing solutions developed within SFI Smart Ocean. The CTD casts are taken at the orange dots labeled as CTD indicated in Fig. 1 in May, October and November 2022 and February 2023. This test facility is run by the Institute of Marine Research as part of the SFI Smart Ocean. Physical ocean sensors, such as CTD, current profilers, oxygen sensors, and turbidity sensors, are deployed along anchored moorings deployed at the North and South rigs, indicated by orange triangles in Fig. 1.

The black triangle represents the dock where we set up the channel sounding experiments as described in Sect. 5. Recently a fish farm about 150 m long has been installed and is indicated as a light blue rectangle. Additional sites may be available for permanent installation of underwater sensors and modems depending on the authorization of local authorities. These points are labeled with letters from A to K.

3. NUMERICAL SIMULATIONS OF THE UNDERWATER ACOUSTIC PROPAGATION

3.1 Sound speed profiles and bathymetry

From CTD casts taken over eight positions with different sea bottom depths, we can obtain the Sound Speed Profiles (SSP), as shown in Fig. 2 for position CTD4, closest to the north rig over the 4 experimental campaigns so far. In general, the largest variability is measured in the first 10 m below the surface.

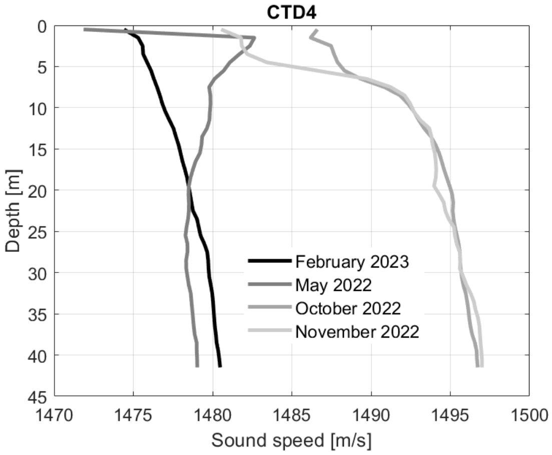
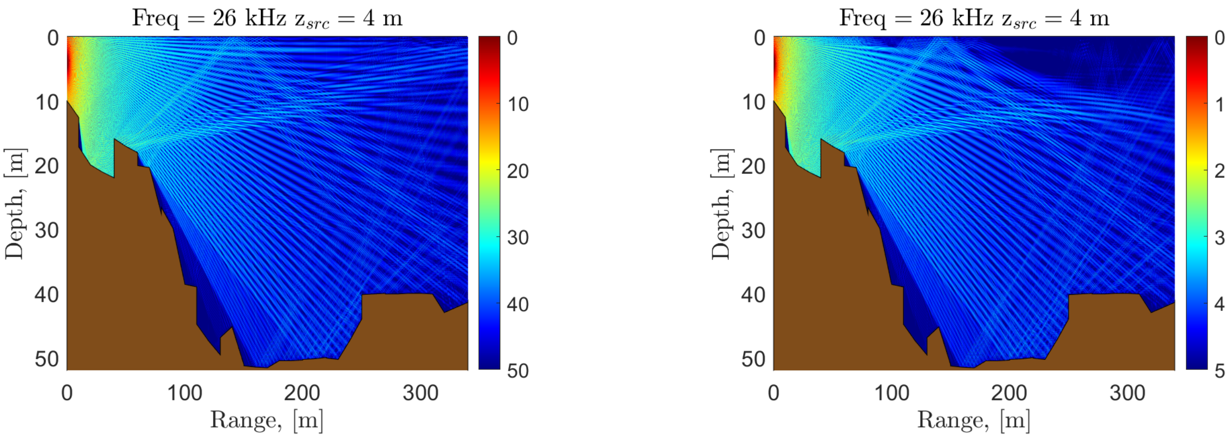


Figure 2: Sound speed profile at CTD4 over the four experimental campaigns represented in different color lines.

This variability of the sound speed profile is a key parameter with respect to how the acoustic waves propagate in the horizontal communication channel and drives deployment parameters such as at which depth the source should be deployed and whether adaptive modem depth would be beneficial.

Bathymetry was taken from the Geonorge map catalog [14] that contains information on coastal bathymetry at openly available resolution. The bathymetry profile can be obtained from the database by pulling the depth data at points along the straight line between two positions expressed in latitude and longitude coordinates. We do not have detailed information about the interpolation methods applied from the underlying bathymetry data to the depth profile extracted from the database, and some artifacts are evident in the resulting bathymetry profiles (see Figs. **??** and 6).



(a) February 2023.

(b) May 2022.

Figure 3: Transmission Loss between the cNODE at the dock and the cNODE at the North Rig. Numerical modeling through Bellhop in February and May. The modem operates at center frequency 26 kHz and was installed at 4 m depth.

3.2 Bellhop numerical acoustic propagation modeling

We apply the numerical propagation ray-tracer Bellhop to understand how the acoustic propagation could be affected by the boundary conditions of an irregular bottom profile and by the season-dependent refraction index represented by the SSP across the water column.

We limit ourselves to 2D modeling, knowing that a 3D model would be a better fit for acoustic propagation in constrained environments such as fjords. Fig. 2 shows the SSP measured by CTD casts in May, October and November 2022, and February 2023. We considered CTD4, which is the closest point to the north rig. The stratification of the water with a warm layer close to the surface in the spring and a cold layer in the autumn is quite evident.

Sound waves are reflected off the sea bottom and ocean surface and refracted when the sound speed varies with depth. Refracted sound waves will always turn or bend towards the region, exhibiting lower sound speeds. For this reason, we can expect that in October and November there will be a surface channel in the upper 5 meters. This is not expected in February and May.

Figs 3a, 3b, 4a, and 4b show the transmission loss predicted by the ray tracer by using the corresponding SSP collected in the indicated month for transmissions from a source placed at 3 m depth from the dock towards the north rig. The emission angles range from $-90°$ to $90°$.

4. EXPERIMENTAL SETUP

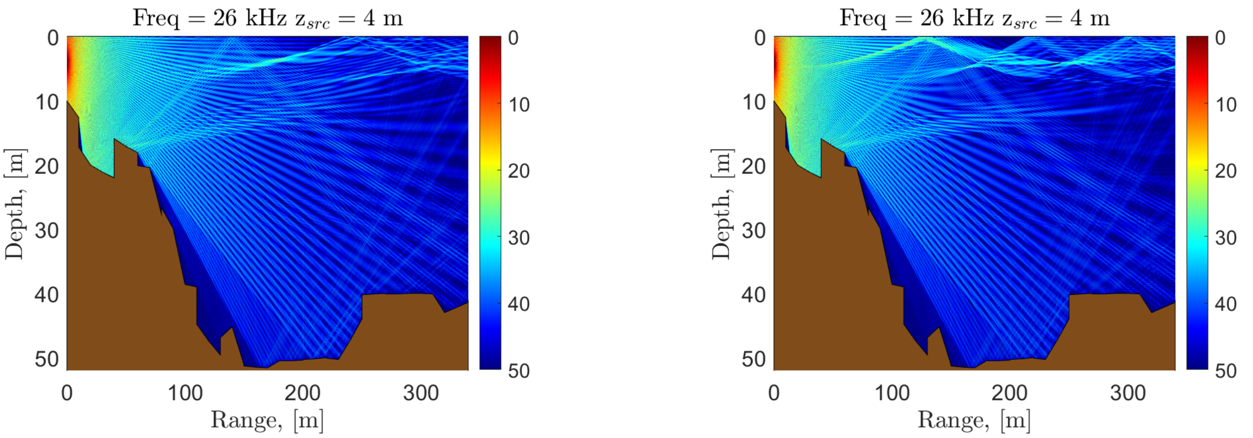
In the following subsection, we describe two experiments performed in the fall of 2022. The first experiment consists of an acquisition system for underwater acoustic channels over the 55-65 kHz band. We used this frequency band because the B&K hydrophone had a resonance frequency for transmission around 60 kHz.

During the second experiment, a communication link between two cNODEs was tested over a few days. The cNODEs were deployed in the black triangle and in the orange triangle called the North rig indicated in Fig.1. Their distance was about 200 m. We ran the acoustic propagation simulations for this scenario, since the effect of the sound speed profile and the bathymetry was also confirmed by the measured communication performance.

4.1 Channel probing signals for 55-65 kHz in October 2022

Fig. 5 represents the channel sounding setup that we used on the dock in October 2022. We transmitted a train of linearly frequency-modulated chirps and m-sequences with symbol duration 0.125 ms for channel sounding. The transmitted signal spanned the 55 to 65 kHz band and a root raised cosine was applied as a window filter with roll-off factor $\alpha = 0.25$.

The B&K 8104 hydrophone was used as a projector. The connected cable was 10 m long and we used the typ-



(a) October 2022.

(b) November 2022.

Figure 4: Transmission Loss between the cNODE at the dock and the cNODE at the North Rig. Numerical modeling through Bellhop in October and November. The modem operates at center frequency 26 kHz and was installed at 4 m depth.

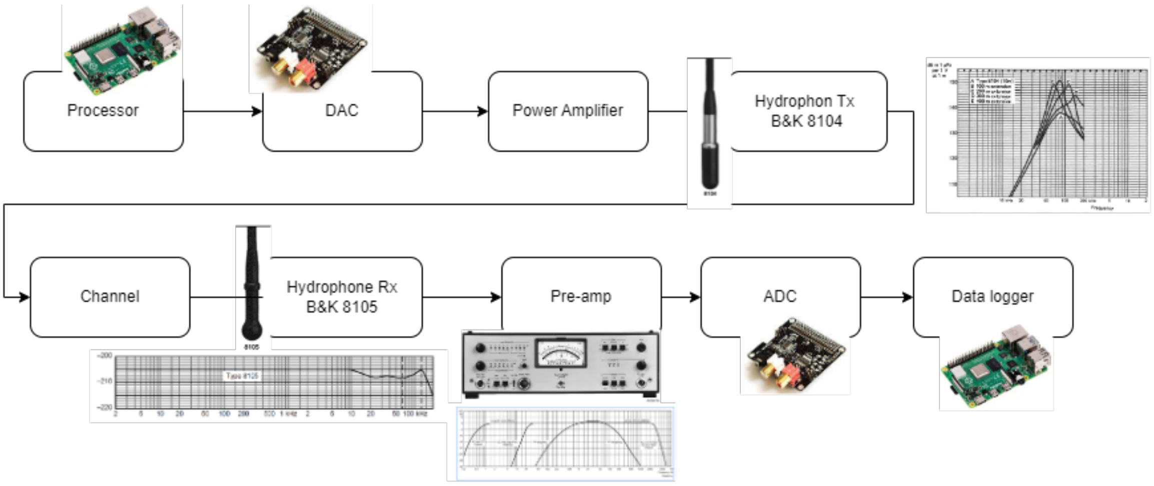


Figure 5: Set up for channel sounding. We used two B&K hydrophones, the PA09 power amplifier, the 2610 pre-amplifier, the HiFiberry DAC/ADC PRO cards with two raspberry pi boards.

ical transmitting response to voltage given in [15] for the 8104 hydrophone. At the frequencies used (55-65 kHz) the typical transmitting response to voltage was not flat and had a source level between 134 and 136 dB re 1 μPa per 1 V at 1 m. If we assumed a flat source level of 135 dB re 1 μPa per 1 V at 1 m, over the frequency of interest, and by amplifying the transmitted signal up to 10 V, then the obtained source level was about 145 dB re 1 μPa at 1 m. With such a low source level we did not expect to reach long distances, so we limited our tests up to the full length of the dock, i.e., 12 m. Higher powers were not considered because we did not want to damage the piezoelectric element of the hydrophone.

The data collected served mainly for proof-of-concept validation rather than characterization of channel statistics. This work was very helpful in better understanding the full chain of development for a software defined modem and allowed us to create an automatic underwater acoustic data logger with our lab instrumentation.

Thanks to this development, we were able to bring the automatic underwater acoustic data logger to the follow-up experimental campaign in November 2022, described in the following section.

4.2 Underwater communications over 20-30 kHz in November 2022

During the subsequent campaign, we integrated a Kongsberg Maritime miniS cNODE modem with an Aanderaa Seaguard II Data Processing Unit (DPU) that integrated several underwater sensors, for example, CTD, ADCP and oxygen sensor, and is cable-connected to a 4G modem on a surface buoy. In this way we were able to communicate remotely to the rig, e.g., to change transmission rate settings.

The objective of this integration was to test the underwater acoustic link between the North rig and the dock and to get a first experience on the system integration.

We ran an overnight test on the bench in the air, with the minimum power level for the acoustic modems, to test the correct integration of the Seaguard II with the cNODE. Only 2 of 5933 packets were lost. This validated the integration, and then we deployed this Seaguard II and the cNODE into the North rig and sent data packets containing CTD data to the node deployed at the dock.

Seaguard II was installed 21 m below the surface and cNODE was installed 24 m below the surface. The transducer of the cNODE miniS modem was deployed to be looking upward. This deployment was dictated by mechanical constraints on the rig and to avoid interfering with an upward-looking acoustic Doppler current profiler that was installed approximately 2 m above the Seaguard II. Fig. 6 represents the transmission loss obtained by Bellhop, using the upward looking transmission angle profile, the modem depth, and the sound speed profile collected in November 2022.

We can see that not much energy is expected to arrive to the dock within the upper 5 m where the other cNODE modem was deployed, and this can explain that the measured success packet rate was around 25 % over transmissions scheduled every 10 seconds for two days. The packets sent from the cNODE at the dock towards the one installed in the North Rig were not logged: they were acknowledgment packets and communication control packets. The transmission source level was set at 184 dB re μ Pa at 1 m.

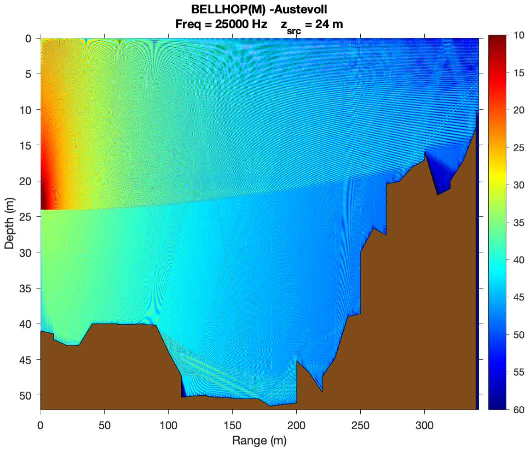


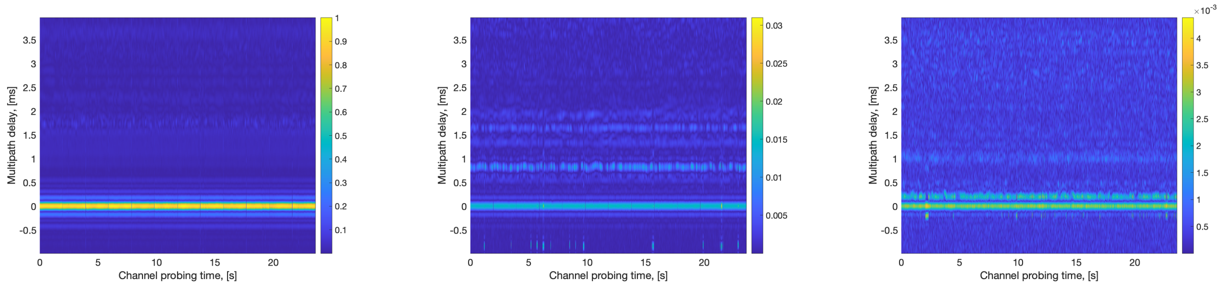
Figure 6: Transmission loss for the deployment of the cNODE in the North rig in November 2022, in the direction towards the dock where the other cNODE was deployed.

4.3 Estimated Underwater channel impulse responses from acoustic data

We used an m-sequence channel probing signal to estimate the channel impulse responses for the channel at 55-65 kHz. We defer from doing the same analysis for the cNODE modem, since we would need to access the channel probing sequence used by the modem, which is a proprietary waveform.

Fig. 7 represents the estimated time series of the channel impulse responses. Each m-sequence (0.0159 s long) was repeated 124 times within 5 seconds (including silence, which is not represented in the plot). Each train of m-sequences was repeated 12 times, leading to approximately 23.62 seconds during which we measured the channel impulse response. In Fig. 7, each channel impulse response is normalized with respect to the maximum value measured at a distance of 50 cm between the transmitter and the receiver. Moreover, each channel impulse response is centered with respect to its maximum. The color bar has different scales in the three figures.

Figs. 7a, 7b, and 7c represent the estimates obtained, respectively, at a distance of 50 cm, 250 cm, and 1200 cm (which was the length of the dock where we installed the hydrophones). The depth of the water was approximately 10 m and the hydrophones were deployed approximately 4 m below the water surface.



(a) 50 cm distance. (b) 250 cm distance. (c) 1200 cm distance.

Figure 7: Time Series of the channel impulse responses estimated with the 55-65 kHz acquisition system for different distances between transmitter and receiver.

5. FOLLOW UP EXPERIMENTATION IN AUGUST AND NOVEMBER 2023

In the following months, three experimental campaigns are scheduled: one in the late spring (beginning of June), one in August during the summer season, which was not represented last year, and the last one in November 2023. CTD data will be collected, and in August we plan to install two cNODEs on the north and south rigs and communicate to a third modem installed in the fish farm structure (indicated in light blue in Fig. 1).

The distances from the middle of the fish farm to the North and South rig are about 280 m and 770 m, respectively. We will schedule transmissions according to a time-orthgonal multiple access scheme, with one transmission per hour at each of the modems so that the batteries of the modems are expected to last for 90 days. We will test the possibility to adapt the power level (three power levels available) and the waveform duration and symbol rates during this deployment.

At the same time, a pair of software-defined modems using projectors provided by Kongsberg Maritime operating in the same frequency bands (20-30 kHz) will be tested. We will be able to operate these additional nodes either along the fish farm or by submerging the systems at authorised locations.

Authorization for the deployment of permanent submerged instrumentation has been requested from the Austevoll municipality for the points indicated by the letters from A to K in Fig. 1 and some of them may be available in the next experimental campaigns.

The main scientific objectives of the following tests will be to evaluate the network data rate that can be achieved by the commercial modems available installed in the area. From the error statistics, we will gain insight into how to better design communication and networking technology for use in these challenging coastal underwater acoustic environments.

Considerations on the management of interference among coexisting communication systems working on the same frequency bands and how to implement them in the area will be drawn once the developed software-defined modem can be deployed in the area.

The iterative innovation method for the long-term evaluation of underwater acoustic communication systems and networking protocols is represented in Fig. 8. The blue blocks represent underwater acoustic propagation modeling and how environmental conditions measured at sea can feed these models. Their outputs are considerations for deployment of commercial modems, indications on how to set the best parameters, and can provide theoretical benchmarks for the performance.

In green, there is the underwater acoustic channel sounder and waveform recorder that we developed and that could be used close to commercial modems. In this way, the received waveforms could be postprocessed by different algorithms at the receiver, for example. Some of these algorithms could receive as input the environmental measurements taken during the experimental campaign.

These post-processing adaptive algorithms could apply to any of the protocol stack layers and are indicated by gray blocks. Finally, the pink blocks represent the commercial baseline communication system for which we log status messages and measure performance.

All these systems feed a comparison block, whereby the benchmarks are the theoretical curve and the commercial measured performance statistics. Any technical de-

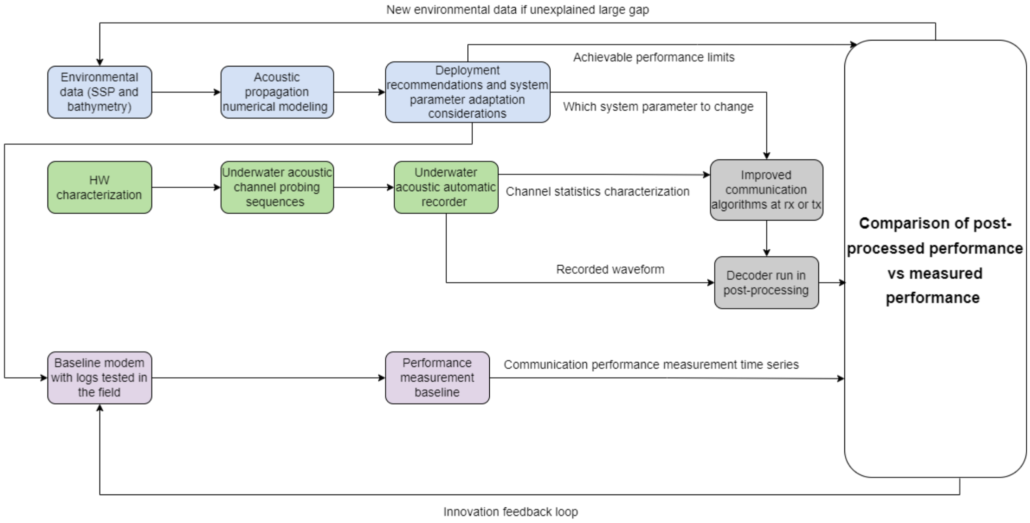


Figure 8: Iterative innovation method for underwater acoustic communication systems and networks in long-term deployments. Environmental measurements, numerical modeling of acoustic propagation and channel sounders, and baseline commercial systems contribute to an innovation feedback loop.

velopment that can make the commercial measured performance move towards the theoretical curve will provide insights on the methods that work best in these constrained environment, and we can then test these novel algorithms in the same area.

5.1 Discussion on lessons learned

During these first two experiences in the field, we developed a channel probing system working in the frequency band 55-65 kHz and an automatic underwater acoustic acquisition system by using off-the-shelf components.

We also tested the integration of an underwater DPU with a commercial modem and collected statistics on the throughput received for the point-to-point link.

Based on these developments, we can summarize the following learned lessons.

- It is useful to have a hydrophone while doing communication system tests in order to verify that the signals are actually sent by the different nodes.
- When using commercial modems, different combinations of sets of parameters can be possible. Finding in each deployment which set is giving the best performance might not be possible after deployment and if needed before, then it may become costly in terms of boat time.
- A systematic way to identify the best set of parameters to use in a given deployment would be highly beneficial.
- Such methods should be implemented directly in modems in an automated way (adaptive modulation and coding).
- This would allow non-experts in underwater acoustic communication to use technology with greater confidence as end users.

6. CONCLUSIONS

In this paper, we presented a method and its implementation for evaluating and enhancing the performance of underwater acoustic communication and networking technology in the context of coastal fjord ocean observation science and industrial fish farming activity. Both these applications require the installation of submerged water quality sensors that need to send back data in quasi-real time. For this, underwater acoustic sensor networks may represent a viable technology, even though they exhibit limitations in terms of reliability and data rates. Within SFI Smart Ocean, there is the possibility to access the same area over several years to test and validate new solutions, especially those targeted to the use cases described above. We then proposed an iterative method by which environmental conditions are fed into numerical acoustic propagation models, and recordings of the acoustic signals can be reused for improving decoders for example. Finally, we should run numerical simulations of network protocols based on the channel statistics collected to compare alternative solutions with those tested in the field.

7. ACKNOWLEDGMENTS

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