EXPLOITING SPATIAL DIVERSITY TO IMPROVE QOS-ENABLED UNDERWATER COMMUNICATIONS

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Abstract: *The bandwidth utilization of untethered underwater vehicles can be optimized by concurrently transmitting data with different Quality-of-Service (QoS) constraints, e.g., high-QoS telemetry data and low-QoS sensor data (such as a SONAR image) in a single transmission. The Multi-Stream Frequency-Repetition Spread Spectrum (MSFRSS) modulation has been developed to support such QoS-enabled underwater communications. This work evaluates MSFRSS performance in practical North Sea conditions. The unidirectional link between a RHIB and a bottom node is studied for single- and multi-hydrophone reception, and for different types of equalization. The potential performance increase for multi-hydrophone reception is illustrated by postprocessing of trial recordings.*

Keywords: *acoustic underwater communications, sea trial, Quality-of-Service levels*

1. INTRODUCTION

There is a growing interest in the use of untethered underwater vehicles to perform safe, sustainable and cost-effective underwater operations. For most applications, the bandwidth utilization of these vehicles can be maximized by concurrently transmitting data with configurable Quality-of-Service (QoS) constraints, e.g., high-QoS telemetry data and low-QoS compressed image snapshots in a single transmission. To support such QoS-enabled underwater communication, the Multi-Stream Frequency-Repetition Spread Spectrum (MSFRSS) modulation was introduced [1]. A short introduction to MSFRSS can be found in Section 2.

Previously, MSFRSS has been tested in a real-time demonstrator in a harbour and a fjord [2]. To evaluate the performance of MSFRSS in offshore conditions, a short North Sea trial was conducted on October 10th, 2018. During this trial, a series of communication and channel-sounding runs were executed to assess the unidirectional link between a RHIB and a bottom node. Details of this trial are discussed in Section 3.

Communication performance of the trial's unidirectional link was evaluated by postprocessing the bottom node recordings (for multiple receiver configurations). In contrast to earlier work, the exploitation of spatial diversity has now also been considered. The different receiver configurations are enumerated in Section 4, followed by their respective communication performances in Section 5.

Conclusions and recommendations are listed in Section 6.

2. MULTI-STREAM FREQUENCY-REPETITION SPREAD SPECTRUM

MSFRSS can be considered as a successor of Frequency-Repetition Spread Spectrum (FRSS) [3]. FRSS is a coherent multiband modulation where all subbands carry the same symbol sequence. This type of redundancy allows for joint equalization of these subbands at the receiver to exploit frequency diversity. In contrast to FRSS, MSFRSS modulates multiple sets of redundant subbands simultaneously. Each set of redundant subbands is called a stream, hence the name Multi-Stream Frequency-Repetition Spread Spectrum (MSFRSS).

To provide different QoS levels using MSFRSS, for each stream (i) its symbol constellation, (ii) its number of redundant subbands, (iii) its training configuration, and (iv) its code rate can be set. Details on the configuration used in the North Sea trial can be found below. An extensive description of MSFRSS, and its key transmitter/receiver operations are given in [2].

MSFRSS configuration

In the North Sea trial, high-QoS telemetry data and low-QoS compressed image snapshots were transmitted simultaneously (Section 3). The transmitted waveform covered a 30 kHz (half-power) bandwidth. This entire bandwidth was evenly divided over eight streams, each encompassing 3.75 kHz. One of these streams acted as high-QoS stream, holding six QPSK-modulated subbands, and the seven other streams were low-QoS streams, each holding three 8-PSK-modulated subbands. The configuration is visualized in Figure 1. For clarity, the depicted subband ordering is sequential. In reality, the distance between subbands is maximized using an objective function.

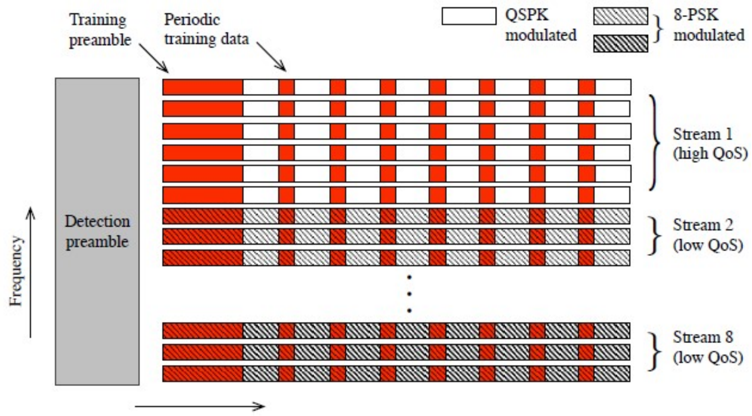


Figure 1: MSFRSS configuration used in the North Sea trial.

3. NORTH SEA TRIAL

To assess MSFRSS in offshore conditions, a NILUS bottom node [3] was deployed on the floor of the North Sea. An anchor was attached to the bottom node to prevent it from crabbing due to the current. Additionally, the node was tied to a surface buoy, for not having to depend on the acoustic release for recovery as this functionality was not 100% reliable in combination with the prototype MSFRSS implementation. The NILUS bottom node (Figure 2) was configured to continuously receive and record with all of its four hydrophones. The acoustic transmitter, broadcasting in the 17-47 kHz bandwidth, was deployed from the RHIB using the onboard crane (Figure 2).

Figure 2: The receiving NILUS bottom node (left) and the onboard crane used for deploying the transmitter (right).

The trial area was located approx. 10 km west of Scheveningen harbour, marked by the leftmost ellipse in Figure 3. The bathymetry in the trial area indicates that the local depths at low tide of the sandy seafloor in the trial area were between 16 and 22 m. During the trial day, on October 10th 2018, the actual depths as measured by the RHIB's echosounder during the bottom node deployments varied between 20 and 21 m, which was confirmed by the pressure sensor of the node. During these deployments, the air temperature was measured to vary between 14 and 15 °C. Wind speeds varied between 5 and 10 kn and there was no rain. The significant wave heights varied between 32 and 48 cm.

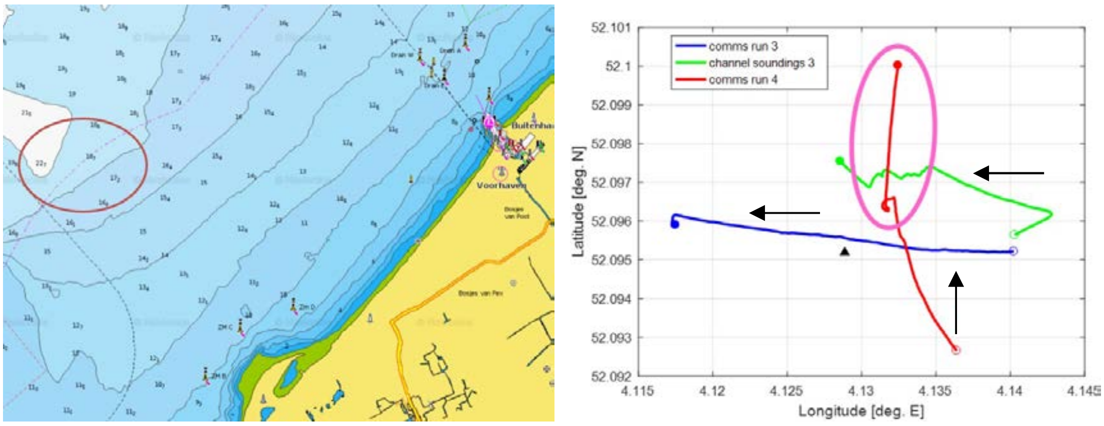


Figure 3: Bathymetry of the trial area (left); courtesy of Navionics. Tracks during the third deployment (right); the bottom node position is depicted by a triangle.

Deployment issues

There were three deployments of the bottom node in the trial area. Unfortunately, the bottom node had fallen on its side during every deployment, probably due to the connection to the surface buoy in combination with a sloping bottom and a strong surface current.

During the three deployments, in total three channel sounding experiments and four communication runs were executed. After on-board analysis of recordings from the first two deployments, the decision was made to stabilize the transmitter (near the end of the third deployment) by bringing in the crane. The latter decreased the Doppler induced by transmitter motion and improved communications results (Section 5). In this paper, only recordings from the third deployment are studied. The RHIB and bottom node positions during this deployment are depicted in Figure 3. Arrows indicate the direction of the RHIB's tracks.

Channel soundings

This section discusses channel soundings captured while sailing an in-bound track, i.e., the RHIB with transmitter was slowly moving towards the bottom node (Figure 3). The movement of the RHIB resulted in a negative Doppler velocity (assuming the sign convention that a positive velocity corresponds to an increasing range [4]). During this track, 16 series of of 4 pulse trains were transmitted and received, with each pulse train being a 10-s sequence of (Linear Frequency Modulated) LFM pulses of 32, 64, 128 and 256 ms. The 32-ms pulse train appeared to be the best fit for the delay-Doppler spread experienced in the channel.

Channel sounding results for the shortest and longest distance during the in-bound track of the RHIB are shown in Figure 4 and Figure 5, respectively. Herein, from left to right, the impulse response evolution, the spreading function, the Doppler spectrum and the power delay profile are shown.

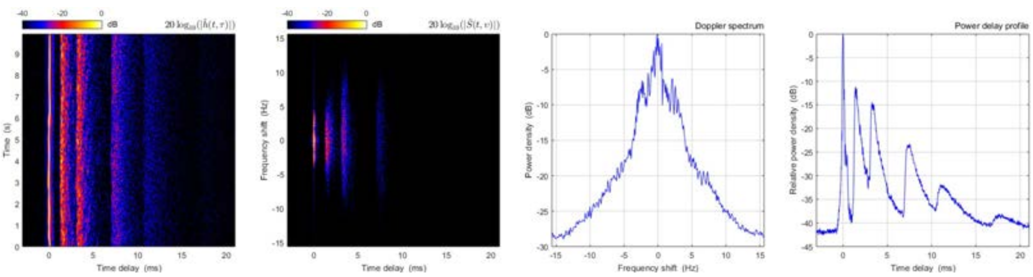


Figure 4: Channel sounding results at approx. 200 m distance.

There is a significant delay spread in both measurements. At 200 m distance, the first arrival is clearly the most powerful arrival. The channel sounding at 900 m seems to present evidence of non-minimum phase behaviour; due to the variation of the propagation speed while travelling through the water, the direct-path arrival arrives later than the reflected arrival.

Also, a relatively large Doppler spread can be recognized for both distances. As the receiver was stationary, this must have been because of (i) the transmitter moving heavily and (ii) reflections from a moving sea surface.

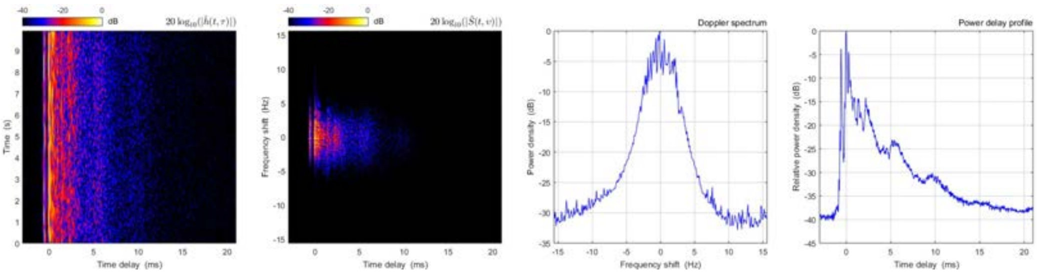


Figure 5: Channel sounding results at approx. 900 m distance.

Communication experiments

In each communication run, MSFRSS was employed to transmit image snapshots registered by an on-board webcam and telemetry data (GPS-NMEA strings) from the boat to the bottom node. Per MSFRSS transmission (Section 2) 96 bytes were reserved for the high-QoS payload (GPS-NMEA string) and 2.9 kB for the low-QoS payload (image data). The duration of each transmission was 4.35 s. The effective data rate of the QPSK/8-PSK configuration is 5630 bit/s.

4. RECEIVER CONFIGURATIONS

Compared to earlier experiments in Trondheim fjord [2], the channel conditions on the North Sea were more challenging. To deal with this offshore environment, instead of only using the top hydrophone channel of the NILUS' tetrahedron array, the MSFRSS receiver was extended to coherently combine all four hydrophone channels. Apart from exploiting spatial diversity, an option to switch the tap update algorithm between Least Mean Squares (LMS) or Recursive Least Squares (RLS) was also added.

Table 1 offers an overview of all receiver configurations and relevant parameters of the respective tap update methods. Herein, the subband equalizer length refers to the span of the feed forward filters per subband. The choice of the subband equalizer length, the LMS step-size parameter and the RLS forgetting factor are based on [2].

Configuration	*Subband eq. length*	*Parameters*	*Receive hydrophone(s)*
SISO-LMS	12.5 ms	0.3 (step-size par.)	top
SISO-RLS	12.5 ms	0.995 (forgetting factor)	top
SIMO-LMS	12.5 ms	0.3 (step-size par.)	all (4)
SIMO-RLS	12.5 ms	0.995 (forgetting factor)	all (4)

Table 1: MSFRSS receiver configurations

5. COMMUNICATION PERFORMANCE

This section focuses on the communication performance for single-hydrophone (SISO-LMS and SISO-RLS) and multi-hydrophone receiver processing (SIMO-LMS and SIMO-RLS).

SISO-LMS and SISO-RLS configuration

Initially, during the first half of the fourth communication run, very few correct (single-hydrophone) demodulations were obtained for the high-QoS payload and none for the low-QoS payload. As explained in Section 3, this was caused by the significant Doppler spread, being amplified by the RHIB's crane deploying the transmitter.

The situation improved significantly when bringing in the crane (Figure 2) and gently streaming the transmitter behind the boat. In Figure 3, the part of the track where receptions improved is indicated by the rightmost ellipse. Having the transmitter behind the boat, most of the high-QoS payloads could correctly be demodulated, but still none of the low-QoS payloads.

SIMO-LMS and SIMO-RLS configuration

After coherently combining all four hydrophone channels, both the demodulation of the low-QoS payloads and high-QoS improved significantly. In the SIMO-LMS receiver configuration, out of the 69 detections (of 76 transmissions; 91%), 64 high-QoS payloads (GPS-NMEA strings) were demodulated correctly (93%). These 64 GPS positions are visualized on top of the track recorded by the RHIB in Figure 6. Apparently, the GPS receiver in the transmit laptop had a coarser resolution than the RHIB's receiver. Assuming that the same source satellites were used, this difference must have been due to a lack of interpolation (e.g., by Kalman filtering) in the laptop's GPS receiver.

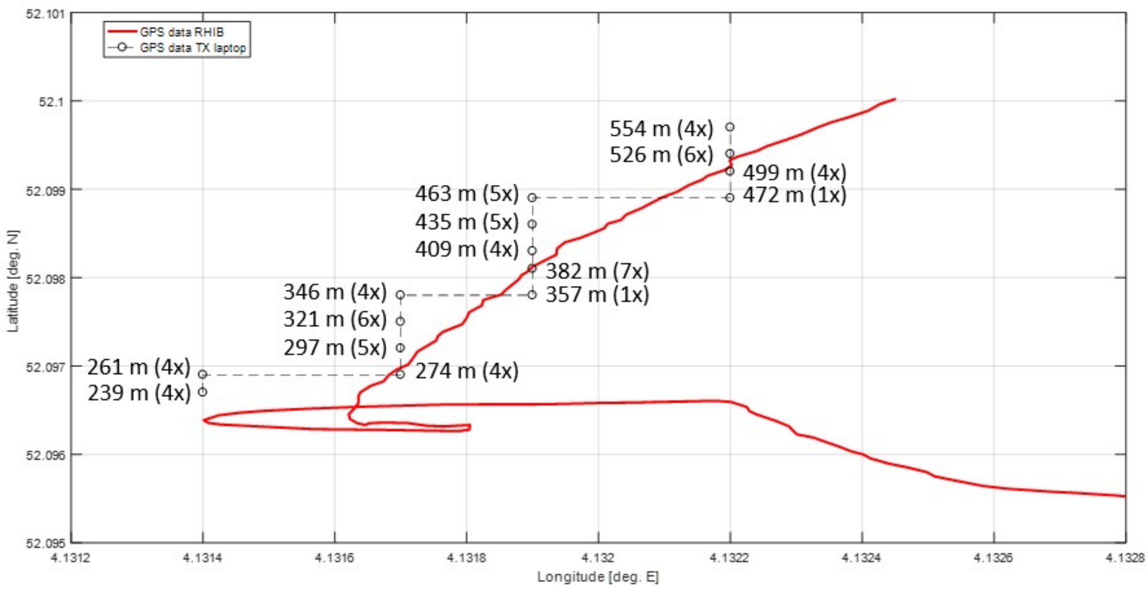


Figure 6: Demodulated GPS positions during the second half of the fourth comm. run.

Results for the demodulation of low-QoS payloads (images) for the multiple-hydrophone configurations are shown in Table 2. For these receptions, SIMO-RLS seems to perform slightly better than SIMO-LMS.

Configuration	*Partially correct image receptions*	*Fully correct image receptions*
SIMO-LMS	30 (43%)	5 (7%)
SIMO-RLS	34 (49%)	7 (10%)

Table 2: SIMO-LMS and SIMO-RLS performance for the low-QoS payload.

The output SNRs for demodulation of the high-QoS and the low-QoS payloads using both SIMO-LMS and SIMO-RLS are shown in Figure 7. In general, the output SNR is a good indicator for equalizer performance [5]. It appeared that, especially for the low-QoS payload, the SIMO-RLS receiver seems to outperform the SIMO-LMS receiver.

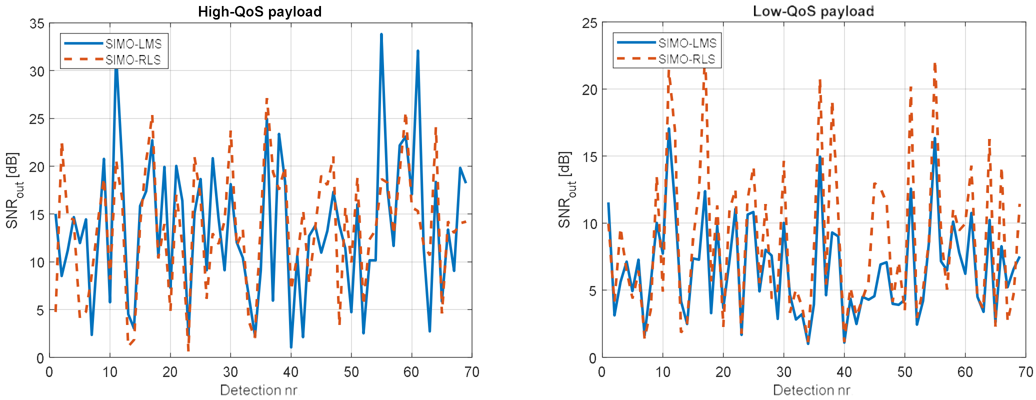
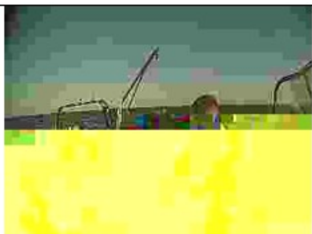


Figure 7: Output SNR comparison for the SIMO processing.

For three distances (321 m, 409 m, 499 m) the MSFRSS demodulation results are shown in Table 3. The respective number of bit errors for the different payloads were calculated using the reference transmissions available from the transmit laptop on the RHIB.

		
321 m, original image	SIMO-LMS: Bit errors high QoS = 0 / 768 Bit errors low QoS = 48 / 20125	SIMO-RLS: Bit errors high QoS = 0 / 768 Bit errors low QoS = 0 / 20125
		
409 m, original image	SIMO-LMS: Bit errors high QoS = 0 / 768 Bit errors low QoS = 43 / 20125	SIMO-RLS: Bit errors high QoS = 0 / 768 Bit errors low QoS = 0 / 20125

		
499 m, original image	SIMO-LMS: Bit errors high QoS = 0 / 768 Bit errors low QoS = 0 / 20125	SIMO-RLS: Bit errors high QoS = 0 / 768 Bit errors low QoS = 12 / 20125

Table 3: MSFRSS demodulation using the SIMO-LMS and SIMO-RLS configurations.

6. CONCLUSIONS

In this work, QoS-enabled underwater communication has been demonstrated for an unidirectional link between a RHIB and a bottom node under offshore conditions. To create QoS diversity, MSFRSS was employed. After stabilizing the RHIB's acoustic transmitter, to decrease the Doppler spread, most single-hydrophone receptions of the high-QoS payloads (GPS-NMEA strings) of the MSFRSS messages could be demodulated correctly.

Reception of the low-QoS payloads (images) required coherent combining of all four hydrophone channels that were available on the bottom node. When using coherent combining and RLS (SIMO-RLS) to determine the equalizer weight updates, approximately 10% of the low-QoS payloads were correctly received, and about 49% partially correct.

Although data rates were smaller than for an earlier demonstration in a fjord (5.5 kbit/s vs. 7.3 kbit/s) [2], the potential of multi-hydrophone reception for QoS-enabled underwater communications in offshore conditions has certainly been demonstrated.

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