CHARACTERIZING THE UNDERWATER ACOUSTIC COMMUNICATIONS CHANNEL IN SHALLOW ESTUARIES AND ITS APPLICATION TO THE DEVELOPMENT OF A FLEXIBLE WIDEBAND MODULATION

Henry Dol[a], Koen Blom[a], Mathieu Colin[a], Mark Prior[a]

[a]TNO, Acoustics & Sonar department, The Hague, The Netherlands

Contact author: Henry.Dol@tno.nl, P.O. Box 96864, NL-2509JG The Hague

Abstract: *Underwater acoustic transducer technology is improving significantly, enabling wideband acoustic communications or the flexibility to shift a narrow communication band to a more benign carrier frequency. In the framework of a European project (ECSEL SWARMs), a single commercial-off-the-shelf transducer covering the 17-47 kHz band was selected and added to an existing underwater acoustic communications system. The upgraded system was consequently used to characterize the underwater acoustic channel by performing channel soundings for the full 30 kHz bandwidth and for several distances and velocities. The experiments were performed in a shallow estuary/river environment in The Netherlands. The results of these experiments show that long-range communication may actually be easier than short-range communication, as long as there is still a direct path and when the multipath is sufficiently damped by many (muddy) bottom interactions. On the other hand, this means that wideband modulations for high-speed communication over short ranges still need a minimum of robustness to cope with the delay-Doppler spreading due to reflections and reverberation. Inspired by these results, a flexible wideband modulation and demodulation technique is developed, which is tested a-posteriori for the measured wideband channels by replay simulations, and compared with the in-situ narrowband communication performance.*

Keywords: *Shallow-water acoustics, underwater acoustic communication, flexible wideband modulation.*

INTRODUCTION

In the past few years, The Netherlands Organization for Applied Scientific Research (TNO), supported by The Netherlands Ministry of Defence, and the Norwegian Defence Research Establishment (FFI) have together developed a robust physical-layer algorithm for underwater acoustic communication – Frequency-Repetition Spread Spectrum (FRSS) – that was successfully tested in various (semi) operational environments and conditions, achieving single-hop ranges over 5 nautical mile (nmi) in the 4-8 kHz band [1][2][3][4]. However, the price that had to be paid for such a robust link is a fairly limited information data rate of the order of 100 bit/s, which is sufficient for command & control (C2) messages with small data payloads (e.g., sonar contacts), but is insufficient for more data-intensive applications such as transfer of images taken by divers or wireless docking of Autonomous Underwater Vehicles (AUVs). Such applications require information data rates of at least a factor 100 higher, i.e., >10 kbit/s, but do not necessarily require as long (horizontal) communication ranges. Single-hop ranges up to 1 nmi are considered sufficient for most high-rate data links.

The present paper explains the process of specifying an appropriate frequency range, selecting a suitable (COTS) transducer and optimizing the physical-layer algorithm for high-rate underwater acoustic communication. The actual algorithm development is explained in another paper [5], whereas in the present paper, the focus is on the characterization of the shallow underwater acoustic environment, which served as inspiration for the design of a flexible wideband modulation and as a concrete means for software testing. The reported research has been conducted partly in the European project SWARMs[1] (Smart and Networking Underwater Robots in Cooperation Meshes).

DESIGN OF A WIDEBAND HARDWARE EXTENSION OF THE NILUS NODE

Together with suitable protocols for media-access control and networking, the FRSS modulation has been implemented on a compact software-defined underwater acoustic modem based on smartphone/tablet technology [1]. This “SoftModem” is the underwater communication device of the NILUS bottom nodes – lightweight underwater sensors developed by FFI [2] – as owned by The Netherlands Ministry of Defence. The modem’s wet end is a subsurface buoy (Fig. 1) hovering above the NILUS frame, about 6 m above the sea floor. The buoy includes the amplifier, the impedance-matching network and the acoustic projector. The receiving hydrophone with preamp is mounted on the tripod structure, approximately 1 m above the sea floor.

Fig. 1: The NILUS bottom node, with software-defined modem (inside upper Delrin container; wet end in special float shape for stability in currents).

After an extensive inventory of wideband transducers available on the market, eventually the omnidirectional Neptune D/26/BB broadband transducer was selected and integrated into the NILUS SoftModem wet end (Fig. 2). Based on (PSpice) simulations, a –3 dB bandwidth of about 30 kHz should be possible for this transducer after some more

[1] Contract 662107-SWARMs-ECSEL-2014-1.

impedance matching, with the frequency band running from approx. 17 to 47 kHz and with a maximum source level of about 185 dB re μPa^{2}m^2. For lower frequencies, the available COTS transducers become too large to be mounted on a compact Autonomous Underwater Vehicle (AUV), and in-band AUV self-noise may then severely degrade the communication performance. For higher frequencies, typical AUV sonars (single/multi-beam echo sounder, Doppler velocity log, acoustic Doppler current profiler, obstacle-avoidance sonar, side-scan sonar, etc.) may interfere significantly, and communication ranges are short due to absorption by sea water.

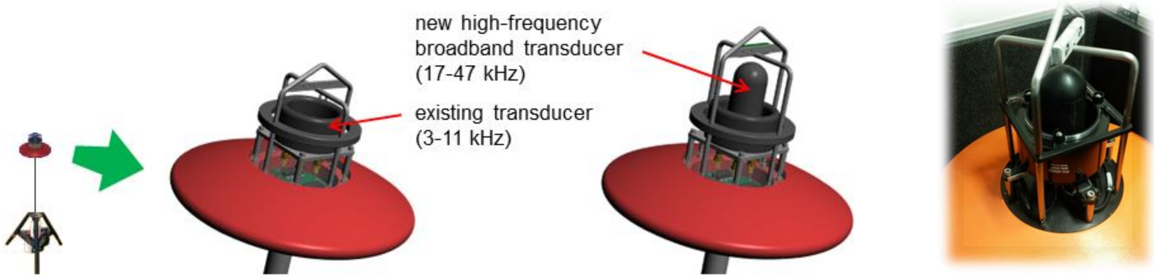

Fig. 2: Extension of the modem wet end with an additional high-frequency transducer.

The actual transmit characteristics of the high-frequency (HF) extension (with impedance matching) have been measured in TNO's anechoic basin (10×8×8 m^3, depth 8 m; Fig. 3, right). The very shallow basin measurements were not conducted at full power to avoid damaging of the transducer by cavitation bubbles.

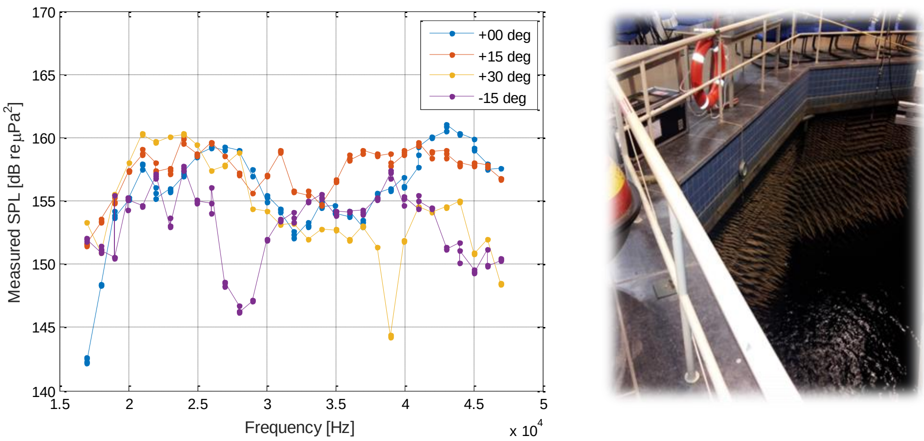

Fig. 3: HF frequency response (left) measured in TNO's anechoic basin (right).

The graph in Fig. 3 provides the measured sound pressure level (SPL) for a fixed transmission power and at a fixed distance from the HF transducer, for various frequencies in the HF band and four vertical angles (30, 15, 0, –15°). Positive angles are upward in the final configuration where the transducer floats above the NILUS node, but for the basin tests the transducer was upside-down and so positive angles were actually downward. Careful processing was needed to separate the direct path from the (surface) reflection in the received signals.

The shape of the frequency response at zero degrees corresponds quite well to the graph provided by the manufacturer in the calibration report. The response is better at +15°, while worse at +30° and –15°. For a scenario where the HF communication is between a bottom node and a vehicle above the node at sufficient horizontal distance, the response between 0-15° is most important. At shorter distances, there will probably also be enough power in the local minima of the frequency response.

For the development of algorithms for high-speed communication in the wide HF band, high-quality channel soundings are required. Next to sufficient signal-to-noise ratio (SNR) at the receiver (>15 dB), this means that the transmitted probe signals should be as spectrally white (flat) as possible. For this purpose, the signals have been frequency-weighted to decrease the local maxima in the frequency response, see Fig. 4. As this goes at the expense of the available power, the weighting is only performed for the channel soundings and not for the actual communications. The receiving equalizer compensates for this.

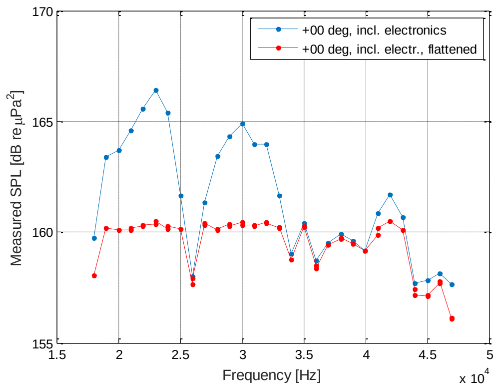

Fig. 4: Unweighted (blue) vs. weighted (red) HF frequency response at 0°. Compared to Fig. 3, the response here includes the modem electronics. Actual in-band variation is ~4 dB (red line).

WIDEBAND CHANNEL CHARACTERIZATION IN SHALLOW WATER

On 22-23 June 2016, a wideband channel-sounding campaign was performed in The Netherlands shallow-water estuary Haringvliet, see Fig. 5. Hereto, a variety of Linear Frequency Modulation (LFM) and Pseudo-Random Binary Sequence (PRBS) probe signals were transmitted and received over several distances, from ~100 m up to ~7 km, and for two relative speeds, one inbound (–3 kn, approx.) and one outbound (+2 kn, approx.). The impulse responses that can be derived by correlating receptions with transmissions provide very useful information about the acoustic communication channel and can be applied in replay simulators, such as FFI's Watermark [6], for a-posteriori testing of communication signals in the frequency band covered by the channel soundings.

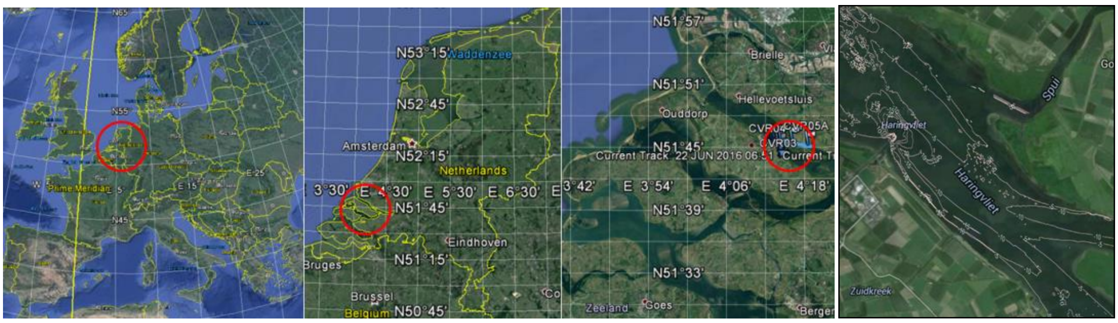

Fig. 5: The Haringvliet estuary (NL). Bottom depth contours are included (right).

The Haringvliet is basically a semi-closed river delta featuring shallow water depths (<20 m), a muddy bottom, fresh water (salinity ~0.1‰) and absence of significant currents, which makes it a suitable environment for first open-water tests. In the specific area where the measurements were performed, the depth was mainly between 10-15 m. The receiving (RX) bottom node was deployed at a local depth of about 12 m, while the transmitter (TX) was deployed from a RHIB at about 5 m below the surface. The sound speed was regularly measured to be around 1,478 m/s (iso-velocity profile). According to weather websites, the air temperature was ~21°C and the wind speed ~4 kn (WSW, Bf 2). It was a dry day on 22 June, while 23 June featured some heavy rain showers (10-20 mm) with thunder.

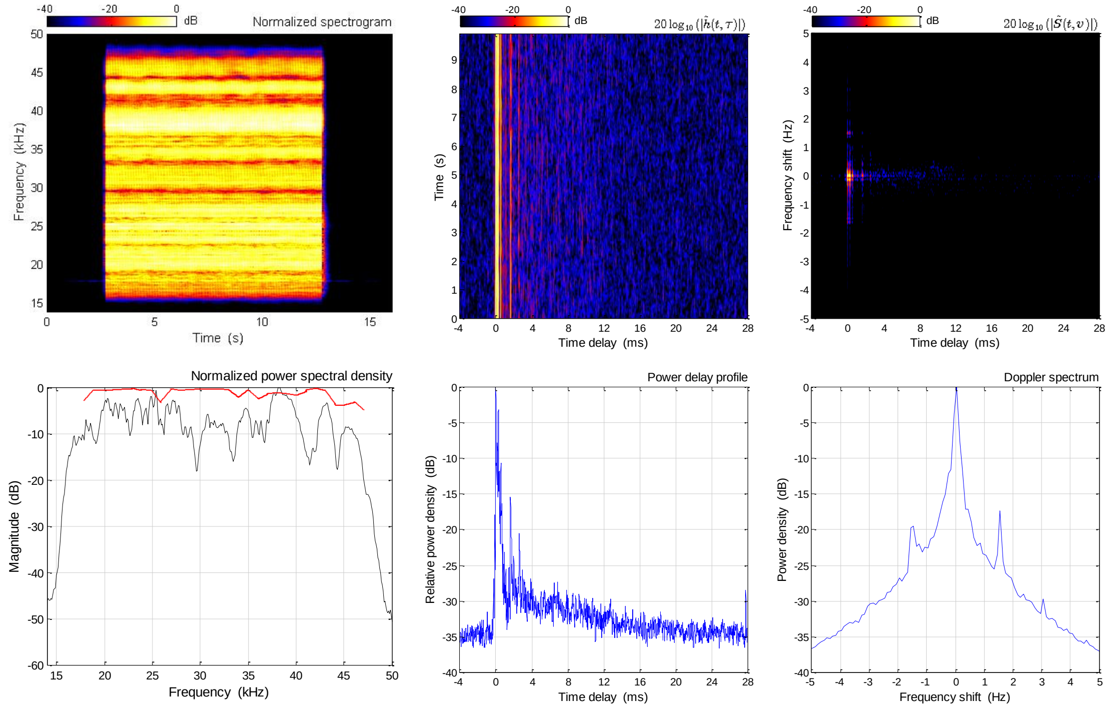

Fig. 6: Channel-sounding results on 22-06-2016 (09:51Z) for 10-s trains of 32-ms LFM pulses transmitted over 0.2 km distance at 0 kn rel. speed (0.002 m/s), with SNR_{in} = 47 dB.

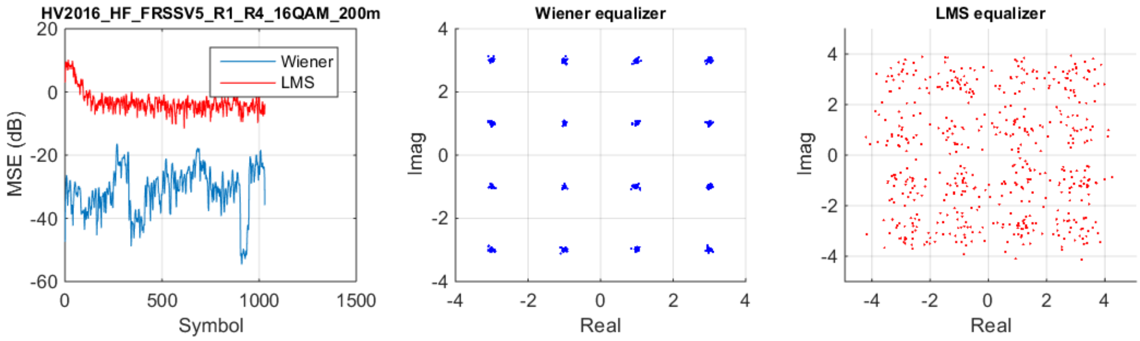

Fig. 7: Preliminary narrowband (30-34 kHz) communication test results at 0.2 km for 16QAM symbol constellations, and FRSS with 3 redundant subbands (SNR_{out} = 14 dB).

Figs. 6 and 8 show, for a short and long distance, the spectrogram (top-left), the power spectral density (bottom-left), the impulse response (top-centre), the power-delay profile (bottom-centre), the delay-Doppler spread (top-right) and the Doppler power spectrum (bottom-right). All levels are normalized. The red line in the power spectral density graphs indicates the transmitted level, and the effects of frequency-selective fading due to constructive and destructive interference are clearly visible in the received levels (black). Frequency-dependent absorption plays a less important role in these fresh waters.

Figs. 7 and 9 show some 'narrowband' communication results for the two channels in Figs. 6 and 8. This concerns the FRSS modulation with 3 redundant subbands, as explained in [1], but shifted from 4-8 kHz to 30-34 kHz, and with the original QPSK symbol constellation replaced by the more dense 16QAM. The middle panels of Figs. 7 and 9 show the constellations of the optimal demodulation results, i.e., when the training sequence would include the entire message. These Wiener results present the upper limit of what can be achieved with (linear) equalization for the considered acoustic channel. The right panels show the demodulation results using the Least Mean Squares (LMS) tap update algorithm of the more practical Decision Feedback Equalizer (DFE) employed by FRSS. The left panels show the convergence behaviour of both the Wiener equalizer and the DFE with LMS, which is quantified by the evolution of the Mean-Square Error (MSE) of the demodulated symbols compared to the transmitted symbols. Note that the Wiener results are a bit 'jumpy', which is because a block-based Wiener equalizer has been used. Figs. 7 and 9 show that there is still a lot to win, e.g., by using the Wiener equalizer for the (initial) training sequence and by updating the equalizer taps with interleaved training symbols using a more progressive algorithm such as Recursive Least Squares (RLS). The latter is computationally more complex and more prone to divergence than LMS though.

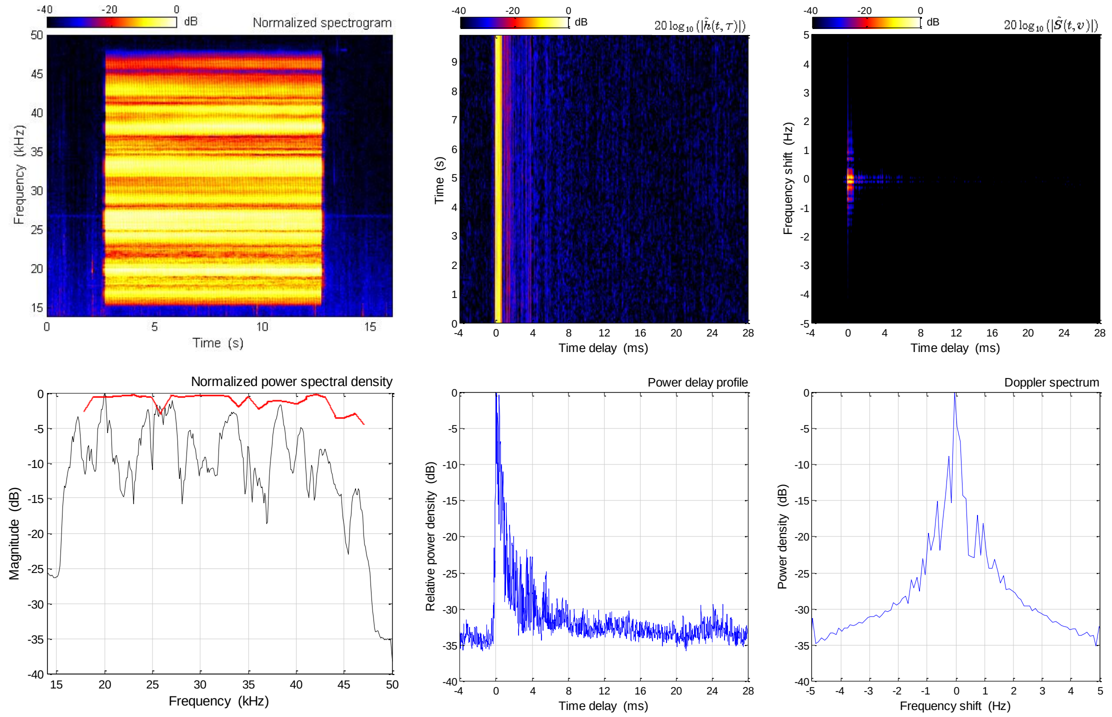

Fig. 8: Channel-sounding results on 23-06-2016 (10:36Z) for 10-s trains of 32-ms LFM pulses transmitted over 7 km distance at 0 kn rel. speed (0.017 m/s), with SNR_{in} = 27 dB.

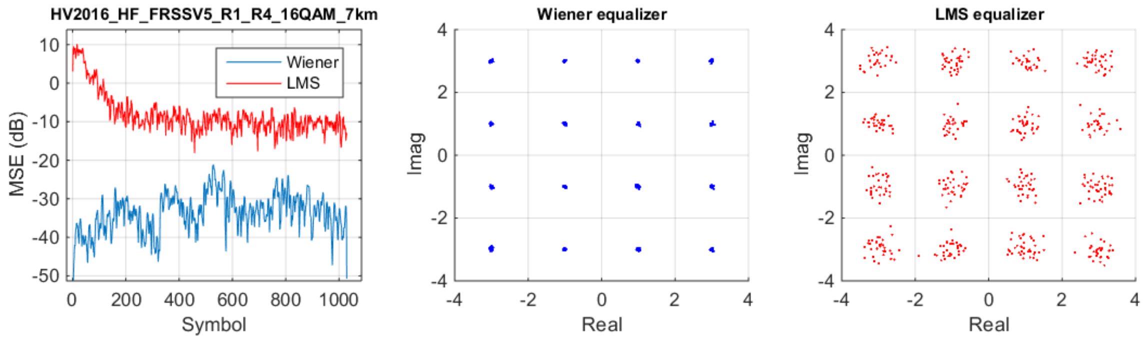

Fig. 9: Preliminary narrowband (30-34 kHz) communication test results at 7 km for 16QAM symbol constellations, and FRSS with 3 redundant subbands (SNR_{out} = 20 dB).

Somewhat surprising, the (narrowband) communication results of the present trials appear to be better for 'long distances' than for 'short distances', as is illustrated by the LMS equalizer results in Figs. 7 and 9 (right panels) which show more concentrated symbol clouds at 7 km than at 0.2 km. This is because of the multipath being attenuated by the many reflections in the shallow water with muddy bottom when the distance increases, which is an acoustic phenomenon called mode stripping. This hypothesis is supported by the channel-sounding results in Figs. 6 and 8, which show that the time spread decreases for increasing distance (middle panels). Furthermore, the attenuation of the arrival peaks in the power delay profile is matched by modelling results for a fine silt bottom. Basically, for sufficiently long distances, only the direct path remains, provided that there is line of sight, no significant stratification and still sufficient input SNR (SNR_{in}), which is easier to deal with by a communications receiver than a short-distance channel rich of multipath and reverberation (clutter). Note, however, that the multipath extinction does not decrease the frequency-selective fading (left panels), which can be explained by observing that the direct path is actually a cluster of refracted rays that are mutually interfering.

An important lesson for wideband / high-rate modulation development, as can be learned from the experiments reported above, is that also for short communication ranges a minimum level of robustness is still needed to cope with the delay-Doppler spreading due to reflections and reverberation. However, the implementation of this lesson will inevitably decrease the information data rate. The challenge will be to find a balance between the required robustness and the maximum achievable data rate. Since this will depend strongly on the channel at hand, a flexible and (autonomously) adaptive wideband modulation is required. The flexibility aspect was investigated in the EU-SWARMs project and a TNO-internal project, and is reported briefly below, while the (smart) adaptivity will be the subject of the European Defence Agency (EDA) project SALSA (see, e.g., [3]).

DEVELOPMENT OF A FLEXIBLE WIDEBAND MODULATION

During the Haringvliet trials, successful narrowband communications were established for effective data rates of about 1 kbit/s, up to 7 km distance and including dynamic scenarios, for the FRSS modulation applying 3 redundant subbands, a 16QAM symbol constellation and a frequency bandwidth of 4 kHz centred around 32 kHz. The first step towards wideband communications is of course an extension of the frequency bandwidth to the full available 30 kHz. Because a simple widening of the 3 subbands will be less robust, because of possible synchronisation and equalization problems for the resulting very short symbol lengths, effort was put into the design of a flexible multi-stream version of FRSS, called MSFRSS. For a single stream, the original FRSS modulation will result, whereas the possibility to have multiple non-redundant streams keeps the individual subbands narrow, while still efficiently using the available bandwidth. Furthermore, the subbands of all streams can be shuffled with each other over the complete bandwidth, for optimally countering the effect of local frequency-selective fading. More details on the development of MSFRSS is provided in [5].

REPLAY SIMULATION TESTS

In total, 12 channels were selected from the Haringvliet dataset for wideband modulation development. To this, 18 more channels were added from a Dutch harbour environment [7][5] and two Scandinavian fjords, resulting in a collection of 30 test channels to be fed to the applied replay simulator Watermark [6]. Although a structural benchmark exercise for all available channels and MSFRSS configurations of interest still has to be performed, the results obtained so far show that information data rates of 10 kbit/s are feasible at a variety of ranges. As an example, when using 20 streams of 2 subbands each and an 8PSK constellation, 81,920 information bits are transmitted in 8.2 s, resulting in an effective data rate of 10 kbit/s. These messages can be received error-free for the 7 km channel in Fig. 8 (SNR_{out} between 10-20 dB, median value 17 dB), while only 1 of the 20 streams contains bit errors (661 of 4,096 bits) for the 200 m channel in Fig. 6 (SNR_{out} between 4-16 dB, median value 13 dB, 4 dB in bad stream).

CONCLUSIONS

In the present paper, results for a selection of channel soundings, narrowband communication experiments and wideband communication simulations (via channel replay) were presented for a short and long range in shallow and muddy inland (fresh) waters. An important observation was that the long-range channel was actually easier for the applied communications receivers than the short-range channel, because only the direct arrival remained after extinction of the multipath by numerous reflections at the muddy bottom (mode stripping effect). This implies that a minimum level of robustness is still needed for short ranges when these channels are rich of multipath and reverberation. The question that arises here, however, is what is the definition of a short range. In shallow waters of max. 15 m depth, as considered in this paper, a 'short' range of 200 m is actually quite long compared to the distance to the most nearby reflecting surface (i.e., the bottom and surface), resulting in a quite complicated impulse response at the receiver.

With the above observation in mind, the redundant multi-band approach, equalizer training and error-correction of the original FRSS modulation [1] was maintained for the short-range high-speed modulation under development at TNO. Instead, the gain in data rate was achieved mainly by a significant extension of the frequency band and by switching to a larger symbol constellation. However, in order to avoid possible synchronization and equalization problems for very short symbols, the subbands were kept narrow and the wide frequency band was filled by multiple non-redundant streams, each consisting of multiple redundant subbands spread over the entire frequency band for optimally countering of the effect of frequency-selective fading (i.e., deep spectral nulls at arbitrary places). At the price of a rather complex bookkeeping, this has resulted in a quite robust high-rate modulation – Multi-Stream Frequency-Repetition Spread-Spectrum (MSFRSS) – that is so flexible that it can also be used to distinguish different Quality-of-Service (QoS) levels within the same message, e.g., the combination of a very robust low-rate C2/telemetry stream and less robust high-rate image data streams (allowing some bad pixels). More information on the possibilities of QoS diversity with MSFRSS can be found in [5].

REFERENCES

[1] H. Dol, M. Colin, P. van Walree, R. Otnes, "How smartphone industry made UComms easier: Moore's law goes underwater," in Proc. OCEANS 2015, Genova, Italy, 2015

[2] R. Otnes, E. van der Spek, M. Colin, H. Dol, C. Solberg, "Easily deployable underwater sensor nodes – the NILUS MK 2 demonstrator system," UDT Europe 2016, Norway, 2016

[3] H. Dol, K. Blom, E. van der Spek, "Experiences with JANUS and efforts towards a common heavy-duty underwater communication stack", in Proc. UCOMMS 2016, Lerici, Italy, 2016

[4] H. Dol, P. Casari, T. van der Zwan, R. Otnes, "Software-Defined Underwater Acoustic Modems: Historical Review and the NILUS Approach," IEEE J. Oceanic Eng., 2016 (early access: http://ieeexplore.ieee.org/document/ 7579629)

[5] K. Blom, H. Dol, M. Prior, "Development of a wideband underwater acoustic modulation providing Quality-of-Service support," in Proc. OCEANS 2017, Anchorage, USA, 2017

[6] P.A. van Walree, F.-X. Socheleau, R. Otnes, T. Jenserud, "The Watermark Benchmark for Underwater Acoustic Modulation Schemes", IEEE J. Oceanic Eng., 2017 (early access: http://ieeexplore.ieee.org/document/7932436); http://ffi.no/watermark

[7] B. Binnerts, K. Blom, S. Giodini, "Analysis of underwater acoustic propagation in a harbour environment and its effect on communication," in Proc. OCEANS 2017, Aberdeen, UK, 2017