WATERMARK: A realistic benchmark for underwater acoustic modems

Paul van Walree, Roald Otnes, and Trond Jenserud

Norwegian Defence Research Establishment (FFI), PO box 115, NO-3191 Horten, Norway
E-mail: {paul.vanwalree, roald.otnes, trond.jenserud}@ffi.no

***Abstract*—WATERMARK is a benchmark for testing, development, and comparison of physical-layer schemes for underwater acoustic communications. Its core is a replay channel simulator driven by at-sea measurements of the time-varying impulse response. WATERMARK is programmed in MATLAB and is initially provided with two (single-receiver) test channels with a run time of 30 minutes each. These channels were measured in Norwegian waters in the frequency band from 10 to 18 kHz. The benchmark can be extended with channels from different environments and frequency bands, depending on the willingness of third parties to perform and make available such measurements.**

***Index Terms*—Acoustic communications, physical layer, benchmark, channel simulator.**

I. INTRODUCTION

Modulation schemes for underwater acoustic communications are plentiful, but realistic performance comparisons are scarce. Modem manufacturers and researchers usually perform their field tests in different environments, and the variation in channel characteristics is large even within a given environment [1], [2]. There are no standard test channels and proposed channel simulators have varying degrees of realism, completeness and availability.

The underWater AcousTic channEl Replay benchMARK (WATERMARK) is a realistic simulation tool which is now made available to the underwater communications community. It is built around the validated FFI channel simulator "MIME" [3] and comes with two test channels to get started.

II. THE MIME CHANNEL SIMULATOR

MIME distorts input waveforms by convolving them with measured channels. Its operation principle is known as channel replay

$$y(t) = \int_{-\infty}^{\infty} \hat{h}(t,\tau)\, x(t-\tau)\, \mathrm{d}\tau + n(t) \ , \qquad (1)$$

where $x(t)$ is the input signal, $\hat{h}(t,\tau)$ the time-varying impulse response, $n(t)$ a noise term, and $y(t)$ the distorted output signal. The quantity $\hat{h}(t,\tau)$ is the measured channel, which is an estimate of the true channel $h(t,\tau)$. The "direct-replay" simulation mode of MIME uses the measured channel $\hat{h}(t,\tau)$ as is, where the maximum simulation time equals the measurement time. A statistical replay mode of MIME generates multiple stochastic realizations of $\hat{h}(t,\tau)$ and can run forever. The realism of direct-replay simulations depends primarily on the quality of the channel estimate. The measurement errors have been well documented in the case of cyclic correlative channel sounders [4], and the combination of MIME and correlative sounders has been well validated [3]. Simulated bit and packet error ratios are close to the corresponding error ratios measured at sea. The stochastic replay mode has also yielded realistic error ratios, but has some limitations regarding the reproduction of non-stationary channels, time-varying delays, and correlated scattering. To guarantee realistic simulations, WATERMARK is released only with the direct-replay mode of MIME. This mode faithfully reproduces all propagation effects reported in [2], including channel non-stationarity, correlated scattering, time-varying delays, and ulta-wideband channels.

III. TEST CHANNELS

The initial release of WATERMARK comes with sounding data for two channels. A shallow stretch of Oslofjorden is denoted by NOF1 (Norway – OsloFjord), with a signaling range of 750 m and a water depth varying between 5 and 16 m. A channel measured on the Norwegian Continental Shelf (NCS1) represents a 540-m link at water depth of 80 m. In both cases, probe signals were transmitted from a bottom mounted sender to a bottom mounted receiver. A correlative sounder [2] was used to process the recorded data for the time-varying impulse response $\hat{h}(t,\tau)$. Table I summarizes experiment conditions and signal parameters.

Both NOF1 and NCS1 consist of sixty successive recordings of $\hat{h}(t,\tau)$, yielding a simulation time of about 30 minutes for each channel. This time is not continuous, because the duty cycle of the sounder was 32 s every 400 s (NOF1) or 32 s every 600 s (NCS1). The recorded data cover periods of about 7 and 10 hours, respectively. Acoustic channels are not stationary over such periods,[1] and it is important, for a fair comparison between modulation schemes, that error statistics are averaged over the entire 30 minutes of available simulation time (See Sec. VI).

Figures 1 and 2 show the impulse response for typical soundings. NOF1 is characterized by a few relatively stable arrivals, followed by fluctuating paths. NCS1 has roughly the same delay spread, but lacks the stable arrivals. This is corroborated by the autocorrelation functions ([2], eq. 5)

[1] An important criterion for the selection of NOF1 and NCS1 is that the channel characteristics did not vary dramatically during these hours.

978-1-5090-2696-8/16/$31.00

TABLE I
EXPERIMENT CONDITIONS AND PROBE SIGNAL PARAMETERS.

	NOF1	NCS1
Environment	Fjord	Shelf
Time of year	June	June
Range	750 m	540 m
Water depth	5–16 m	75–80 m
Transmitter	Bottom mounted	Bottom mounted
Receiver	Bottom mounted	Bottom mounted
Signal type	LFM chirp	Pseudonoise
Center frequency	14 kHz	14 kHz
Bandwidth	8 kHz	8 kHz
Tracking period	128 ms	32 ms
Number of snapshots	256	1024
Signal duration	32.6 s	32.6 s
Cycle time	400 s	600 s
# cycles	60	60
Probe signal SNR	> 35 dB	> 35 dB

plotted in Fig. 3. The autocorrelation of NOF1 drops to a value of 0.8 and then remains constant, implying that stable paths carry 80% of the acoustic energy. The curve for NCS1 on the other hand drops to zero. The coherence (half) time is of order 100 ms.

Note that NOF1 is measured with a 128 ms delay coverage, but that Fig. 1 only shows the first 32 ms for comparison with NCS1. A full analysis of the NCS1 soundings reveals a moderate degree of aliasing [4] in both delay and Doppler, which is unavoidable with cyclic measurements of acoustic channels with long, diffuse tails in the delay profile and/or Doppler spectrum. However, the presence of this measurement error appears to have little effect on the realism of the WATERMARK simulations. Figure 4 shows a validation result for a few tested

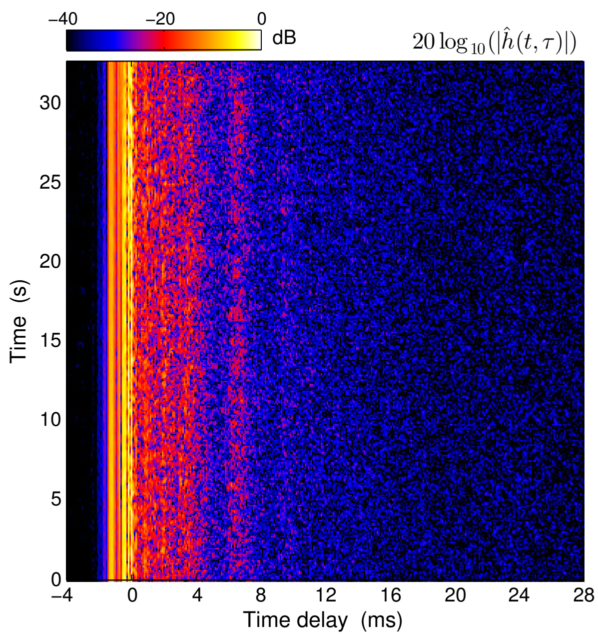

Fig. 1. Magnitude of the time-varying impulse response for the first sounding of the NOF1 deployment.

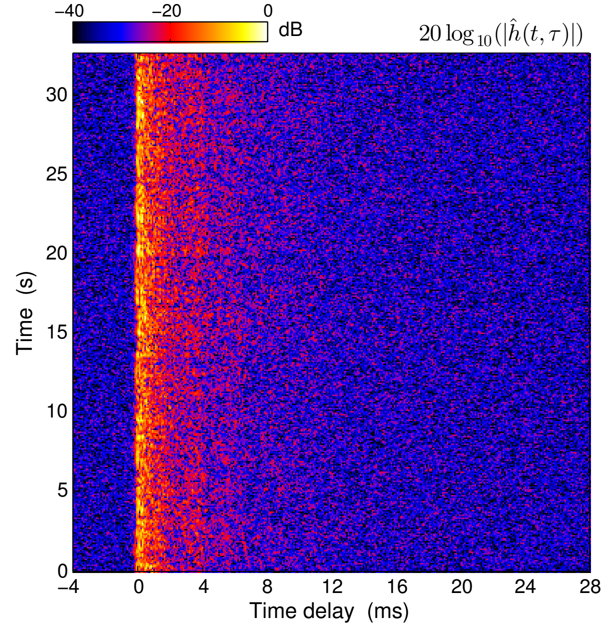

Fig. 2. Magnitude of the time-varying impulse response for the first sounding of the NCS1 deployment.

communication schemes, using the validation methodology of [3]. These schemes are JANUS[2], direct-sequence spread spectrum (DSSS), and 8-ary phase-shift keying (8PSK). JANUS uses frequency-shift keying and energy detection, DSSS uses a chip equalizer and phase detection, and 8PSK is a high-rate scheme with turbo equalization. The JANUS and DSSS implementations are described in [6] and 8PSK is a scheme from [7] adapted to the 10–18 kHz band.

The validation involves 300 probe signals and communication packets, which were transmitted alternatingly in the NCS1 set-up. Recorded communication packets were demodulated, and 300 additional packets were "WATERMARKED" with the recorded probe signals. Measured and simulated packet error ratios are close for JANUS and DSSS at 80 bits/s, which coincidentally also have a similar performance in this channel. Both the oceanic channel and the simulated channel are too difficult for 8PSK.

IV. TRANSFER FUNCTION

The measured impulse response naturally includes the frequency responses of the acoustic waveguide, the employed hardware, and the probe signal. The pseudonoise probe signal in Table I is a cyclic m-sequence with a root-raised cosine pulse shape with roll-off factor 1/8. The correlative sounder applies a filter matched to this m-sequence, which results in a raised-cosine spectrum after the filter. At a chip rate of 8000 chips per second, this spectrum is flat between 10.5 and 17.5 kHz, and has –6 dB points at 10 and 18 kHz. The chirp probe in Table I was identically weighted.

[2]This is not the JANUS standard [5], but an early development version.

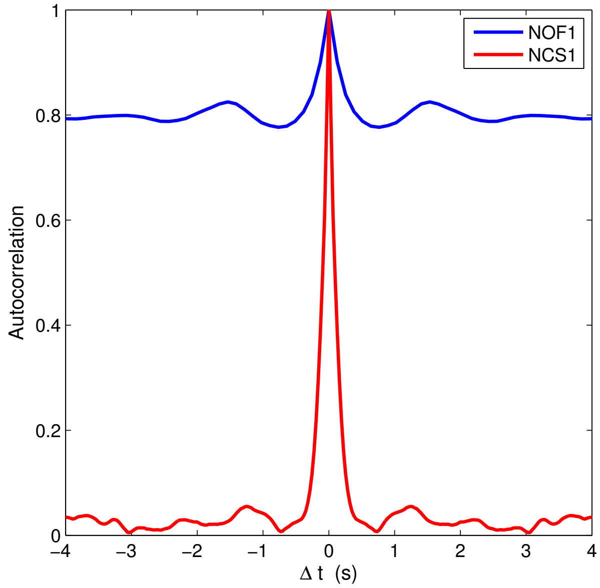

Fig. 3. Channel autocorrelation function of characteristic NOF1 and NCS1 soundings.

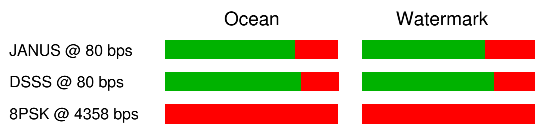

Fig. 4. WATERMARK validation for NCS1. Green is the fraction of packets received without bit errors, red the fraction with one or more errors.

The transfer functions of the channel, the sounder hardware, and the probe signal are superimposed on one another. With WATERMARK driven by NOF1 or NCS1, the resulting signal distortion between 10.5 and 17.5 kHz is entirely due to the channel and the hardware, whereas the fall-off below 10 and above 18 kHz is mostly due to the probe signal. It makes no sense to apply WATERMARK to signals with a nominal bandwidth exceeding that of the probe signal, in this case 8 kHz, simply because there is no response beyond the spectrum of the probe signal.

Thus, with the initial test channels NOF1 and NCS1, modulation schemes can be tested in the band 10–18 kHz. Schemes using a different band should be adapted, because WATERMARK will not adapt to these schemes.

V. DOPPLER EFFECTS

The nominal Doppler shift is removed from the probe signal time series before channel estimation, whereas Doppler spread is preserved in the channel estimate. The Doppler shift is reinserted after the channel replay, so that all Doppler effects experienced by the probe signals are passed on to signals put through WATERMARK. The nominal Doppler shift may be a real Doppler shift, due to platform motion, or an artificial Doppler shift, due to a clock frequency mismatch between sender and receiver, or both. In NOF1 and NCS1 there is only a small apparent Doppler shift, since all instruments were bottom mounted. This shift is preserved in simulation, because the objective is to mimic the effects of both the acoustic channel and realistic hardware imperfections. Note that Figs. 1, 2, and 3 show channels with the nominal Doppler removed.

VI. PRINCIPLE OF OPERATION

The actual channel simulator is MIME, which applies channel replay (Eq. 1) to input signals $x(t)$ provided by the user. WATERMARK is a shell around MIME dealing with interfaces and bookkeeping tasks. The working method is described in detail in the user's manual [8]. A short summary is as follows.

The user generates a communication packet in the band of the desired test channel, with a signal length that cannot exceed the length of the employed probe signal. The user also specifies the sampling rate of the signal and the number of information bits. WATERMARK takes the input signal and convolves it with the measured channels. WATERMARK starts filtering while repeating the packet until the end of each sounding, as illustrated by Fig. 5. The channel estimate $\hat{h}(t, \tau)$ is confined to the same time-frequency regime as the probe signal, and simulation is only possible where there is signal energy in Fig. 5.

Spacing between successive packets is needed to avoid reverberation of one packet into the next one. The minimum required spacing equals the probe signal tracking period. Figure 6 exemplifies the number of independent packets as a function of packet length for NOF1 (i.e, for 60 probe recordings of ≈32 s and a 128-ms tracking period). Acoustic modem signals typically have a duration of a few seconds, yielding several hundred independent packets.

The benchmark enables a fair and realistic comparison between communication schemes. Another application is studying the effect of different parameter settings of a given scheme. Because the test channels are non-stationary, error ratios (or other metrics such as receiver output SNR) should be averaged over all packets delivered by WATERMARK for a given test channel. The result is to be interpreted as a mean performance over the given deployment time.

VII. ADDITIVE NOISE

Packets filtered by MIME are stored and available for further processing. WATERMARK can provide the packets with white Gaussian noise at a specified E_b/N_0 value, or without noise. In the latter case, users can add their own preferred noise types. Comparison of error ratios against E_b/N_0 has the least potential for confusion, because comparisons against the acoustic SNR (ratio of signal power to noise power, measured in the frequency band of the signal) involve the signal bandwidth, for which different researchers use different definitions. Note that the computation of E_b/N_0 uses the number of information bits provided by the user. Overhead due to, e.g., training and coding should not be included.

The packets delivered to the user have a few seconds of silence/noise at the start and at the end, and the precise start time varies between packets. This is done because detection

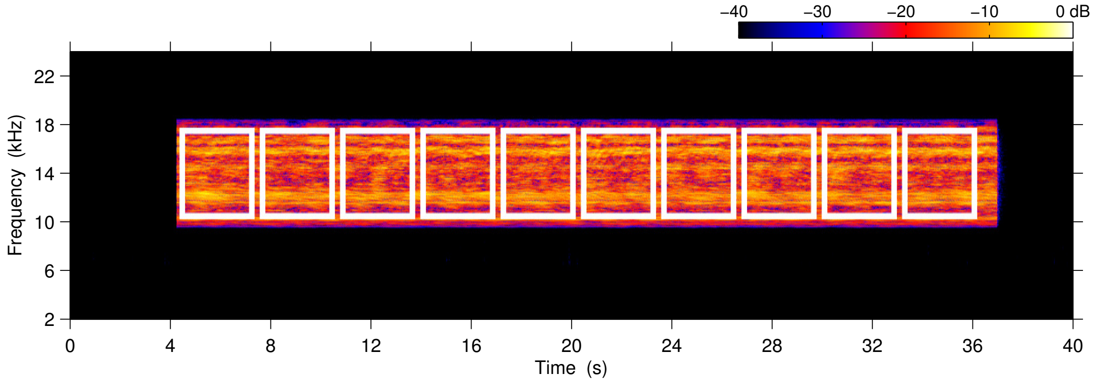

Fig. 5. Spectrogram of a recorded NOF1 sounding signal with hypothetical communication packets outlined in white.

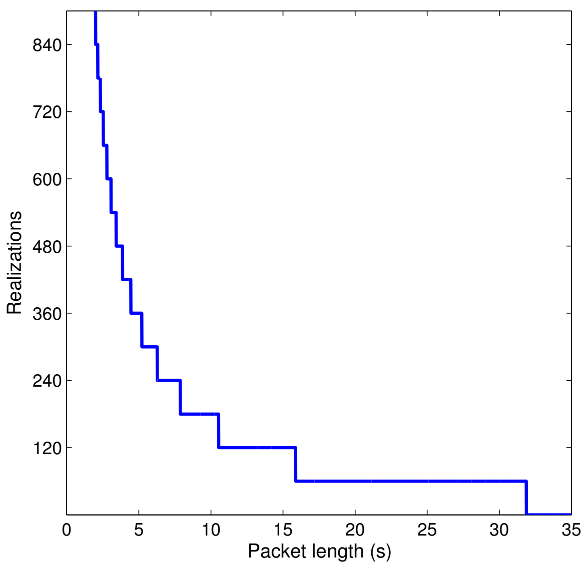

Fig. 6. Example of the number of independent packets as a function of the packet length.

and synchronization is an essential task of acoustic modems. Receiving packets with an unknown arrival time is more difficult than demodulating packets with a fixed (known) arrival time. WATERMARK aims to enable a realistic comparison of autonomous receivers.

VIII. Summary and Conclusion

A tool is made available for realistic benchmarking of underwater acoustic communication schemes. The initial release comes with two test channels measured in Norwegian waters, in the 10–18 kHz band, and with bottom-mounted senders and receivers. Other environments and frequency bands can be simulated by adding channel measurements to the archive, using the WATERMARK channel format [8]. Channels between moving nodes are also supported. Support for hydrophone array reception will be considered for future versions. The community is heartily invited to perform suitable channel measurements, and to make new test channels publicly available following quality checks and successful validation.

With WATERMARK and associated test channels publicly available, modulation schemes and receiver algorithms for underwater acoustic communications can be presented with their WATERMARK performance. This will finally enable meaningful comparisons between results from different groups working in this field.

IX. Availability

Watermark is available for download from the FFI website [9] and may be freely distributed.

X. Acknowledgments

Kongsberg Maritime is thanked for assistance with the channel soundings. The benchmark was partly developed in the European research project RACUN (Robust Acoustic Communications in Underwater Networks) with partners from Germany, Italy, the Netherlands, Norway and Sweden.

References

[1] J. Preisig, "Acoustic propagation considerations for underwater acoustic communications network development," in *WUWNet'06*, Los Angeles, California, USA, September 2006.
[2] P. A. van Walree, "Propagation and scattering effects in underwater acoustic communication channels," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, pp. 614–631, October 2013.
[3] R. Otnes, P. A. van Walree, and T. Jenserud, "Validation of replay-based underwater acoustic communication channel simulation," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, pp. 689–700, October 2013.
[4] G. Matz, A. F. Molisch, F. Hlawatsch, M. Steinbauer, and I. Gaspard, "On the systematic measurement errors of correlative mobile radio channel sounders," *IEEE Trans. Commun.*, vol. 50, no. 5, pp. 808–821, May 2002.
[5] J. Potter, J. Alves, D. Green, G. Zappa, I. Nissen, and K. McCoy, "The JANUS underwater communications standard," in *Proceedings of IEEE UCOMMS 2014*, Sestri Levante, Italy, September 3–5 2014.
[6] P. van Walree, R. Otnes, G. Zappa, and J. Potter, "Comparison between JANUS and DSSS in Norwegian waters," in *UAM 2011*, Kos, Greece, June 2011, pp. 1545–1552.
[7] R. Otnes and T. H. Eggen, "Underwater acoustic communications: long-term test of turbo equalization in shallow water," *IEEE J. Ocean. Eng.*, vol. 33, no. 3, pp. 321–334, July 2008.
[8] P. van Walree, R. Otnes, and T. Jenserud, "The WATERMARK manual and user's guide," FFI-rapport 2016/01378, Forsvarets Forskningsinstitutt, 2016.
[9] "The Watermark acoustic modem benchmark," www.ffi.no/watermark, [Online from October 2016].