FIELD TESTING OF A SPREAD SPECTRUM ACOUSTIC MODEM WITH SPARSE CHANNEL ESTIMATION

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ABSTRACT

This paper describes the field testing of an underwater acoustic (UWA) modem in three distinct underwater environments: in the 5–7 m depth waters off the Goleta Pier in California, in the shallow 2–5 m depth waters of Viapahu Lagoon of Moorea, French Polynesia, and in a coral bommies field in Viapahu Lagoon. The modem employs M-ary direct-sequence spread-spectrum (DSSS) signaling, with joint detection and channel estimation performed by the matching pursuit (MP) algorithm. Our programmable DSP implementation of MP is shown to effectively estimate sparse multipath in real time. The current design employs a 24 kHz carrier and 7.8 kHz bandwidth to achieve a 161 bps data rate. Field tests show bit error-rates (BERs) $\leq 10^{-2}$ are achievable in varied underwater environments at up to 440 m range with multipath spreads on the order of 9 msec.

Index Terms— Matching pursuit, underwater acoustic communication, spread spectrum

1. INTRODUCTION

Field test results in three different underwater environments for an underwater acoustic (UWA) modem using direct-sequence signaling are presented here. In contrast to M-FSK, the DSSS waveform is instantaneously wideband, providing robustness to frequency-selective multipath, and here the use of M-ary DSSS signaling precludes the need for precise phase-tracking.

M-FSK modems [1] use narrowband tones with duration much greater than the multipath spread, thus eliminating ISI. To reduce the effects of ISI and frequency-selective multipath, equalizers [2] and direct-sequence spread-spectrum modulation [3] have been employed. In comparison with DSSS combined with QPSK and QAM modulation, in the UWA modem discussed here detection is accomplished using a bank of M MP-based filters, where $M = 8$ for testing purposes.

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Each of the filters employs the MP algorithm [4, 5] to estimate the multipath channel under each symbol hypothesis. The MP-based filter yielding the smallest residual corresponds to the symbol decision, and is thus an approximate Generalized Multiple Hypothesis Test (GMHT). Thus a phase-locked loop to track the phase from symbol-to-symbol is not required. The full GMHT-MP implementation was detailed in [5, 6].

The UWA modem tested here was designed for underwater telemetry in a short-range (< 500 m) shallow water channel, where multipath spreads can easily extend to 10 msec [3, 7]. The target bit rate is 161 bps, which is adequate for conductivity/temperature/depth (CTD) measurements in Eco-Sensing applications. The current modem operates with a bandwidth of 7.8 kHz at a 24 kHz center frequency, with a data rate of 161 bps.

2. HARDWARE

Details of the modem prototype hardware, a combination of commercial off-the-shelf systems including the TI C6713 DSP evaluation board, systems assembled from standard components (e.g. amplifiers), and custom-made transducers, were previously discussed in [8, 9]. System power during field tests was supplied by lead-acid secondary cells (Pb/PbO_2). Ten watts electrical power drove the transmitting transducer, roughly translating to 2 watts acoustic power. Assuming spherical spreading and the reference sound intensity in water to be $6.7 \times 10^{-19} \frac{\mathrm{W}}{\mathrm{m}^2}$, the source level was approximately 176 dB re μPa during testing.

3. EXPERIMENTAL RESULTS

In this section we describe the series of underwater experiments designed to evaluate the performance of the underwater acoustic modem prototype. The UWA modem test series is grouped by testing environment and physical setup changes, which number three total (Series A–C).

The transmitter sent the same fixed message for each test in a series, where a total 10320 message symbols, divided into

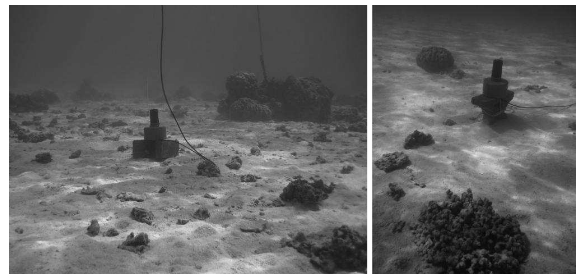
240 packets, was generated according to a discrete uniform distribution. The field testing transmit waveform, 8-ary DSSS using 56-chip truncated Gold sequences, was sent at a rate of 6000 chips per second. Synchronization on the receiver end used 8 training symbols at a time between message symbols in a packet.

While the modem's performance evaluation was mostly based on uncoded symbol error rate (SER), channel coefficient vector estimates generated by the MP algorithm were used to measure environment information in the form of multipath intensity profiles (MIPs) and Doppler spectra.

3.1. Test Environment

Three series of tests were conducted underwater in different environments. Test Series A took place along the Goleta Pier in California, with the transducers, spaced 182 m apart, suspended 10 m from the top of the pier handrail down < 1 m into the water. Wooden planks were used to set the transducers 0.5 m away from the pier pilings, and ocean floor depth ranged from 5–7 m where the transducers were submerged. Series B testing occurred in a 2–5 m depth region of Viapahu Lagoon of the French Polynesian island of Moorea at a 440 m range, with the transducers anchored to concrete blocks that were sunk to the lagoon floor. Test ranges were 330 m and 440 m, with few path obstructions. Series C tests were conducted at 50 m in a coral bommies field in Viapahu Lagoon. Fig. 1 shows the different test environments.

(a)



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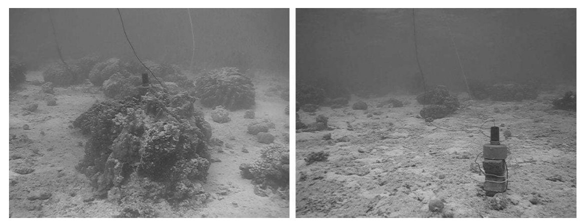

(c)

Fig. 1: Test environment:(a) Series A – Transducers suspended from Goleta Pier, California; (b) Series B – Viapahu Lagoon testing at 330m and 440 m; left - transmitter transducer; right - receiver transducer. (c) Series C – Bommie field testing in Viapahu Lagoon; left - transmitter transducer set on coral bommie; right - receiver transducer set on lagoon floor.

3.2. Test Series A: Transducers hung from Goleta Pier in Goleta, CA

Test results at the Goleta Pier with the receiver and transmitter transducers spaced 182 m apart are documented in Table 1. The N_f column in Table 1 either shows "Est." for MP-based channel order estimation, or a fixed number N_f of assumed paths. Additional columns include uncoded SER, Doppler spread, and the range of paths actually cancelled by the modem in column N_f range, in addition to the mean number of paths cancelled. A representative multipath intensity profile for Series A is shown in Fig. 2.

With SNR at 8.55 dB and a measured total in-band noise level of 119 dB re μPa in the noisy pier environment, the modem averaged $< 10^{-2}$ uncoded SER, while Doppler spread averaged 3.3 Hz. The high Doppler spread was largely caused by the transducers being suspended by rope from the top of the pier and thus undergoing significant motion underwater.

3.3. Test Series B: Anchored transducers in Viapahu Lagoon, 330m and 440 m range

For Test Series B, SNR was measured to be 21.8 dB at the 330 m tests, and 17.9 dB at the 440 m tests, with total noise levels 110 dB re μPa and 108 dB re μPa respectively. Table 2 lists the test results for Test Series B.

The modem averaged $< 10^{-2}$ SER at both distances, and this time with the transducers anchored down Doppler spread averaged 0.4 Hz, or 0.03 Hz when discounting Tests 1-2 in Series B. As shown by the representative multipath intensity profile in Fig. 3, the multipath spread when counting consistently appearing paths generally stayed within 2 ms.

Also of note is the periodic disturbances that are present in nearly all the multipath intensity profiles of this series, and show up as short sections of fluctuations in the otherwise stable channel estimates. They occur, in Fig. 3, with a period of between 2500 to 3000 symbols, or near 0.02 Hz. Such low frequency disturbances are not thought to come from internal sources, and may come from wave motion or elsewhere in the lagoon environment.

3.4. Test Series C: Anchored transducers in Viapahu Lagoon coral bommies field, 50 m range

Test Series C occurred in a coral bommies field region of Viapahu Lagoon, where the sandy bottom lagoon floor was dom-

Table 1: Test Series A Results

Test	N_f	SER	Doppler Spread (Hz)	N_f Range	Mean N_f
1	Est.	3.9×10^{-4}	3.422	1–2	1.01
2	Est.	1.3×10^{-3}	2.314	1–2	1.02
3	4	5.5×10^{-3}	3.384	3–4	1.00
4	4	1.6×10^{-3}	4.204	3–4	4.00
5	1	1.1×10^{-2}	2.858	1	1
6	1	4.3×10^{-3}	2.893	1	1
7	2	9.7×10^{-5}	4.676	2	2
8	3	0	3.487	3	3
9	6	1.9×10^{-4}	5.146	3–6	6.00
10	Est.	0	2.479	1	1
11	Est.	0	2.435	1–2	1.01
12	Est.	1.1×10^{-4}	2.371	1–2	1.00

Table 2: Test Series B Results

Test	Range (m)	N_f	SER	Doppler Spread (Hz)	Mean N_f
1	330	Est.	1.98×10^{-2}	1.468	1.15
2	330	Est.	3.1×10^{-3}	2.810	1.18
3	330	5	1.8×10^{-3}	0.022	1.15
4	330	5	6.3×10^{-3}	0.023	4.95
5	330	5	0	0.044	4.96
6	330	5	0	0.039	4.95
7	330	3	0	0.026	3.00
8	330	3	0	0.024	3.00
9	440	Est.	6.0×10^{-4}	0.030	1.12
10	440	Est.	6.0×10^{-4}	0.044	1.20
11	440	3	1.21×10^{-2}	0.032	3.00

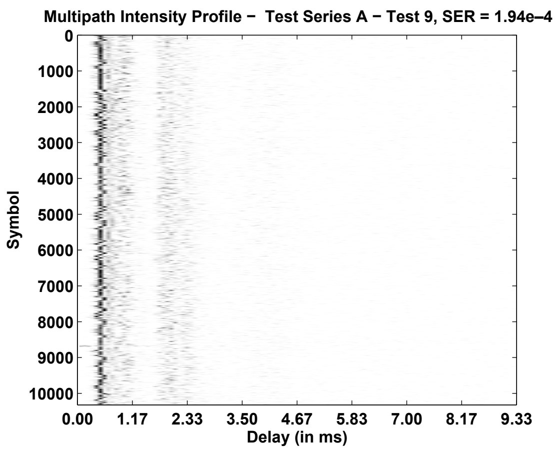

Fig. 2: Goleta Pier: Series A Test 9 multipath intensity profile, N_f = 3–6.

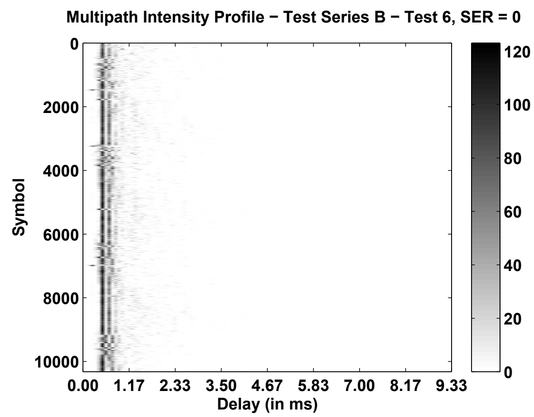

Fig. 3: Multipath intensity profile: Series B, Test 6 at 330 m with anchored transducers and fixed N_f = 2-5.

inated by closely spaced coral bommies. No SNR measurements are available, but it is thought to be high ($>$ 20 dB) due to the short range. The total noise level in band was 114 dB re μPa. A noise spectrum plot shown in Fig 4 demonstrates that the noise was not white.

Table 3 lists the Series C test results. Note that Test 1 shows a high SER of 8.8×10^{-1}, but in that test configuration both transducers were set on the lagoon floor, surrounded by towering coral bommies. A direct path between receiver and transmitter transducer was unlikely under these conditions. Once the transmitter transducer was placed higher (see Fig.1(c)), SER dropped down to zero. Again, Series C, just like Series B, is characterized by low Doppler spread, averaging 0.03 Hz after excluding Test 1.

A typical multipath intensity profile for Series C is shown in Fig. 5. A faint line indicating a weak path is detected near 4.9 ms, with an even weaker path at 5.6 ms, implying a greater multipath spread in the Series C environment. Periodic disturbances previously noted in Series B multipath intensity profiles also appeared in Series C, but with increased frequency. The disturbances now occur once every 1200 to 1400 symbols, or roughly 0.04 Hz, twice the frequency of the disturbances in Series B.

4. CONCLUSIONS

Presented here were the test results of an implementation of matching pursuit (MP) as the signal processing core for joint detection and channel estimation, in three distinct underwater environments. DSSS waveforms, combined with MP estimation, provided robustness to frequency-selective multipath, as well as online channel sounding during communication.

The modem averaged $\leq 10^{-2}$ uncoded SER in the presence of occasionally high Doppler spread ($>$ 1 Hz) over all three test series. These field test results indicate the modem

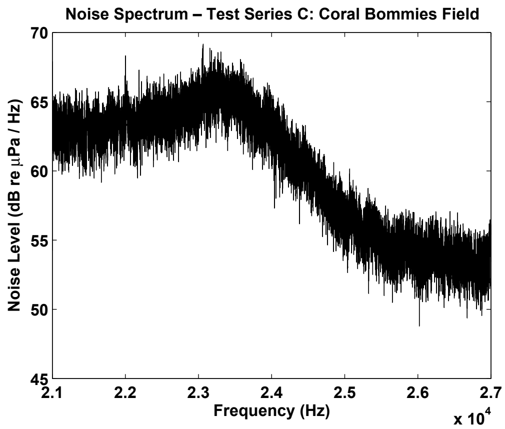

Fig. 4: Series C noise spectrum.

Table 3: Test Series C Results

Test	N_f	SER	Doppler Spread (Hz)	N_f Range	Mean N_f
1	Est.	8.8×10^{-1}	6.097	1-8	1.32
2	Est.	0	0.022	1	1.00
3	Est.	0	0.020	1	1.00
4	5	0	0.022	2-5	4.98
5	5	0	0.033	2-5	4.98
6	3	0	0.061	2-3	3.00
7	3	0	0.020	2-3	3.00

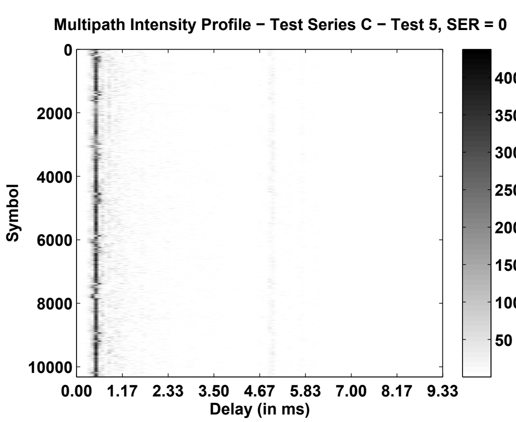

Fig. 5: Multipath intensity profile: Series C, Test 5 at 50 m with anchored transducers and fixed $N_f = 2 - 5$.

provides a solid foundation for a robust solution to underwater ecological sensing applications.

5. REFERENCES

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