High-Rate Acoustic Communications for Ocean Observatories–Performance Testing Over a 3000 m Vertical Path

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Abstract—**The viability of acoustically-linked, long-term ocean sensing is dependent on the power efficiency of the communications system. Energy storage in the deep ocean remains costly despite advances in battery technology, and thus, maximizing data throughput at constant power is an important goal. In preparation for future deep-water applications, a test was recently conducted in 3000 m water to measure the performance of a communications system using a number of different signaling techniques. The signals included BPSK, QPSK and 8-PSK modulation with data rates up to 15000 bits per second. Several receivers were used, including directional transducers, both baffled and un-baffled, as well as a small omnidirectional array. Reliable communication at up to 15000 bps using 7.5 W at the transmitter was achieved. The baffled directional receiver offered the best performance, while the omni-directional array provided approximately 50% less throughput. Source-receiver motion was found to impact system performance and results using an improved Doppler tracking and compensation method are described. Details of the results using various modulation methods and receiver combinations are discussed and their performance extrapolated to full-ocean depth as an aid to the design of future ocean observatory links.**

I. Introduction

A new generation of ocean observatories, which will provide a long-term presence for oceanographic and geological sensing have recently been proposed. These observatories fall into two categories, cabled to shore and buoyed. For buoyed observatories two options for data telemetry to the surface exist, one uses a cable with electrical conductors for power and data, the other uses inexpensive wire rope for the mooring, and an acoustic link for data. While acoustic links cannot replace high-bandwidth, hard-wired links, they are feasible for low to moderate bandwidth applications including ocean bottom seismometers.The acoustic link eliminates the potential for communication failure due to conductor fatigue, and an equally important advantage is that it is possible to add new sensors into the observatory without adding cables.

The scientific utility and cost-effectiveness of a deep-ocean observatory equipped with a battery-operated acoustic modem depends to a great extent upon the power required to reliably transfer data to the surface. The goal of the present design work is a system which will provide telemetry for deep-ocean instruments at roughly 5000 bits per joule at 3000 m depth, and 2000 bits per joule at 6000 m. To telemeter two Gbytes per year from 6000 m at an efficiency of 2000 bits per joule requires approximately 200 alkaline D cells, which is very practical in terms of both size and cost.

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High-rate vertical-channel communication systems have been deployed operationally by several organizations over the last 15 years. These systems use phase-coherent modulation, directional transducers and adaptive equalization to achieve throughput suitable for high-bandwidth sensors. The first high-rate vertical communication link was developed to transmit compressed still images from the SHINKAI 6500 manned submersible to the surface [1]. The system used a carrier frequency of 20 kHz, 8 kHz of bandwidth and QPSK modulation [2]. The reported data rate for the system was 16 kbits per second and no error-correction was employed since the compression technique is robust to occasional bit errors. Particular care was taken in the design of the projector to achieve the desired bandwidth and beamwidth. The result was a directional transducer with 35° beamwidth capable of providing 197 dB source level using 18 Watts [2]. A second high-rate vertical communication link called TIVA [3] was developed in France for use with a compressed still-image system. TIVA used a 53 kHz carrier and differential BPSK to achieve 19.2 kbits per second, but the high carrier frequency (which provides wide bandwidth) limited the effective range to about 2000 m.

A number of innovations in low-power acoustic modem hardware and efficient receiver algorithms have been made over the past several years, thus motivating new implementations of high-rate vertical communication systems with increased efficiency. These enhancements in modem technology prompted the test described here, which is an effort to measure achievable efficiency levels under realistic at-sea conditions.

The material in the paper is organized as follows. In section II the the approach to modulation and coding is discussed and signals used in the test are presented. In section III the receiver algorithm is reviewed, in section IV the transmitter and receiver hardware are described, and in section V the test results are presented and then implications discussed.

II. Modulation and Coding

Acoustic propagation channels vary significantly in complexity and it has been found that one signaling method cannot offer reliable communication under all conditions. Based on this observation, a scalable methodology, which maintains a constant bandwidth while varying both the dimensionality of the signal constellation and the error-correction coding rate, has been developed. The signal constellations used during the test described here include BPSK, QPSK and 8-PSK. The source bandwidth and the symbol rate were 5000 Hz, so that the data rate varied from 5000 to 15000 bits per second. Higher-order constellations such as 16-QAM may also be accommodated.

The three different signal constellations utilize different error-correction coding in order to optimize the link for different situations. The BPSK packets use a low-rate block code (rate 0.16) which is appropriate for low-SNR or extreme multipath conditions. The QPSK data packets employ a rate 0.69 block code, while the 8-PSK packets are trellis-encoded with a rate 2/3 convolutional code. All packets use concatenated coding schemes. The BPSK and QPSK signals use a Reed-Solomon outer code while the 8-PSK uses a high-rate BCH outer code with interleaving between the two layers.

III. The Receiver

The vertical underwater channel is benign in comparison to the horizontal channel, primarily due to the lack of boundary interaction. While there is a modest amount of distortion in the vertical path from temporal and frequency dispersion, these effects are minor compared to the inter-symbol interference (ISI) experienced in shallow-water where the range to depth ratio is large. While the delay spread in the vertical channel is short, potentially large Doppler shifts due to motion between the source and receiver do exist. In addition, the channel impulse response will vary, though at a slower rate than in the horizontal case.

The receiver designed to operate under these conditions is similar to that used for horizontal communications [4]. The main difference is that the receiver in the horizontal channel must adjust for a wide range of delay spreads, while in the vertical channel the delay spread is small and has less variability. As a result, the vertical system is easier to design and more robust in operation.

A. Equalizer

The receiver algorithm is based on a Decision-Feedback Equalizer (DFE) with 2nd order phase-locked loop [4]. The receiver employs a fractionally-spaced feedforward filter which removes the acausal ISI and performs fine-scale timing recovery. The feedback filter cancels residual inter-symbol interference and provides improved performance in a frequency-selective channel. The receiver includes a concatenated code with the inner layer of error-correction performed within the DFE. This takes advantage of the coding gain and reduces the likelihood of contaminating the receiver with erroneous decisions. The feedforward and feedback filters are updated jointly, using the recursive least-squares (RLS) or the adaptive step-size least mean-square (LMS) algorithms as described in [7].

The receiver is designed to be single or multi-channel. In the results described here the DFE is operated in single-channel mode with the directional receivers and in two-channel mode with a small omni-directional array.

B. Doppler Tracking and Compensation

The Doppler shift observed at a receiver below a surface buoy or vessel varies depending upon the steepness of the waves and their rate of motion. Large, steep waves will move a buoy vertically at speeds of up to 4 m/sec and may produce accelerations of up to 3 m/sec^2 at Sea State 6. While the 2nd-order phase-locked loop tracks the phase changes accurately, in order to achieve the SNR necessary for high-rate, bandwidth-efficient signaling, the resulting time dilation or contraction must also be measured and removed. Methods developed for Doppler compensation with fast-moving underwater vehicles have traditionally assumed that, while the Doppler shift may be large, it is constant over at least a few seconds. Thus the Doppler is measured once at the start of a packet and the time-scale change removed via re-sampling prior to equalization [5]. While this method works well with constant Doppler, it can fail when the Doppler shift changes quickly. One solution is to make the packets very short, but when high accelerations are expected, the added overhead reduces efficiency and wastes energy.

A more effective solution is to continuously measure the Doppler and modify the sampling rate accordingly. An efficient means for doing so has been developed [8]. The modified receiver estimates the time scale change by first differentiating the phase tracked by the PLL and then scaling the resulting slope to estimate the interpolation rate. Re-sampling is performed by an efficient filter-bank approach as described in [8].

IV. Equipment

The Utility Acoustic Modem (UAM), developed at Woods Hole for use in oceanographic instruments, buoys and underwater vehicles was used as the transmitter. It is compact (circuit board size is 3 by 8 in.) and relatively low power. For this test it was packaged in a deep-water housing and mounted within an aluminum cage as shown in Fig. 1. The transducer was mounted to the side in order to minimize interference from the cage and lowering cable.

The transducer was a mass-loaded piston with a 60°

conical beampattern. The amplifier was an efficient class-D switching design. Using a step-up transformer and 33 mH matching inductor, a source level of approximately 194 dB was achieved while providing 5 kHz of usable bandwidth at a carrier frequency of 15 kHz. The total power consumed by the amplifier in driving the source was 7.5 W.

Fig. 1. Transmit electronics in pressure case and directional projector mounted to side.

Fig. 2. Directional mass-loaded piston receiver encased in foam baffle to reduce the effects of surface noise and reflections.

At the surface, several types of receivers were used. While prior experience has shown that baffled, directional receivers may offer best performance, certain geometries or applications may be best served with omnidirectional receivers. For comparison, data was taken using both types of transducers. The receivers used were:

1. Directional mass-loaded piston. This receiver was suspended approximately 8 m below the surface. The front-to-back ratio of this transducer is 10-15 dB.
2. Directional mass-loaded piston mounted in a closed-cell foam baffle in order to further reduce the effects of surface reflection and noise. The baffle increases the front-to-back ratio to 15-20 dB. The assembly is shown in Fig. 2. The baffled transducer was also placed approximately 8 m deep.
3. A pair of broad-band omnidirectional hydrophones with 30 cm vertical spacing suspended 4 m deep.

All signals were amplified and filtered, then stored to digital audio tape (DAT) for later analysis.

V. Test Description and Test Results

The test was conducted in January 2000 at 36 26.9 N, 122 34.9 W. The charted water depth was 3100 m. The modem was lowered using the vessel's hydro-wire and recordings were made continuously from all four receiver channels. The winch was paused at different depths in order to allow recording of stationary data. The weather at the site was good with low, long-period swells, slight chop and moderate winds.

A. Directional Receiver Performance

The signal-to-noise ratios observed on the directional receivers were very good at all depths. The results at the maximum range are of primary interest and thus the analysis presented here includes only the 3000 m data. The impulse response at the two directional receivers is shown in Fig. 3. The response at the baffled transducer shows a very clean structure with late arrivals more than 30 dB below the main peak. The impulse response of the un-baffled transducer shows a surface bounce at 0.012 sec. The amplitude of the surface bounce is about 15 dB below from the main arrival, but the reflected energy is scattered over several milliseconds. The same signal on the baffled transducer is over 35 dB down. Both of the receivers show additional energy at 0.13 seconds which is due to reflections from the sea floor below the transmitter.

The signal-to-noise ratio for 8-PSK modulation at the output of the equalizer is shown in Fig. 4 for both the baffled and un-baffled receivers. The baffled receiver processed using the RLS algorithm offers the best performance, with over 20 dB output SNR. For 8-PSK, a symbol SNR of 20 dB translates to approximately 15 dB E_b/N_o, which in turn provides a probability of error which is less than 10^{-6} [6]. The un-baffled receiver is 4 dB worse due to the inter-symbol interference caused by surface reverberation, and the resulting 16.6 dB symbol SNR provides 10^{-4} error probability.

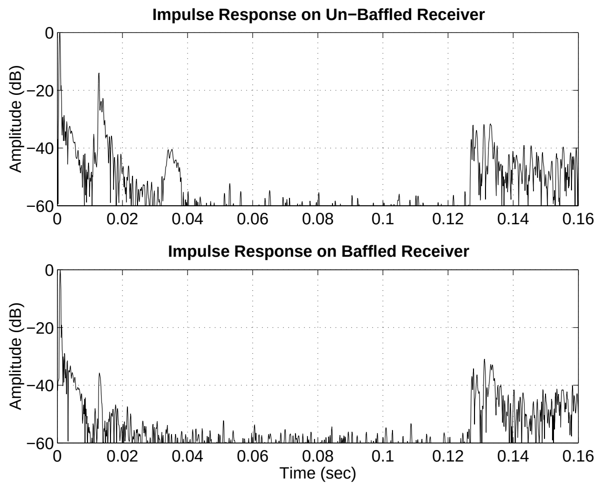

Fig. 3. Impulse response measured at the surface on the baffled and un-baffled directional receivers. The main arrival is normalized to unity and placed at 0 sec on the scale.The un-baffled transducer shows several reflections from the surface, the strongest of which is about 15 dB below the main arrival. The same reflection observed on the baffled receiver is reduced by over 30 dB. The reverberation at 0.13 seconds is caused by reflections from the seafloor which is 100 m below the transmitter.

In comparing the two different update algorithms, the RLS offers 2 dB better performance than the LMS algorithm. As described in [7] it is typical for the RLS algorithm to out-perform the adaptive LMS for certain channels, providing that the RLS forgetting-factor λ is selected correctly. The output SNR for the baffled receiver using LMS is 18.7 dB, which implies an error-rate of 10^{-5}. However, when LMS is used with the un-baffled receiver the SNR drops by 4 dB, and the resulting output SNR corresponds to a bit-error probability of 10^{-3}, which is unsatisfactory for most applications.

The use of baffling on the receiver brings a significant performance advantage and ensures a low error-rate for both LMS and RLS. The nominal efficiency (based on uncoded 8-PSK) is 2000 bits per joule at 3000 m. The RLS algorithm provides 2 dB additional link margin which can be used to increase the density of the signal constellation. The use of a higher-density constellation such as 16 QAM would increase the data rate from 15000 to 20000 bps while maintaining the 5 kHz bandwidth. The efficiency would then increase to 2700 bits per joule. High-rate trellis encoding of the QAM signals could be used to provide immunity to occasional errors at a small expense in throughput The un-baffled receiver offers acceptable performance using the RLS algorithm, but the 4 dB difference in output SNR impacts reliability and throughput significantly.

The QPSK and BPSK signals received using the directional transducers offer similar SNR. Since these signals require much lower SNR per symbol for low error rate performance, their reliability is even higher than the 8-PSK. Though the lower-rate signals are not needed with the directional receivers, their improved performance at low SNR is important when the omni-directional array is used, as described in section V-D.

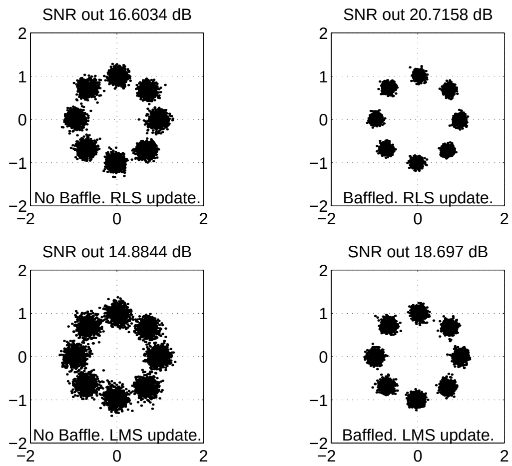

Fig. 4. Equalizer output for both the baffled and un-baffled directional receivers using the RLS and LMS algorithms. The baffled receiver processed using the RLS algorithm offers the best performance, providing an estimated error probability better than 10^{-6}.

B. Performance of Adaptive Doppler Processing

Movement of the vessel during the experiment created up to 1 m/s relative motion between source and receiver. The rate of change of the motion is sufficient to demonstrate the importance of adaptive Doppler processing. An example of the time-varying phase shift and resultant time-scale factor is shown in Fig. 5. At the start of the packet no Doppler shift is observed, but almost immediately the phase slope increases as the relative motion begins. At its peak the motion is 1 m/s, which corresponds to a time-scale change of approximately 0.1%. However, the time-scaling shown in Fig. 5 changes continuously, and thus will require accurate tracking in order to preserve signal fidelity.

The performance of equalizers with, and without, adaptive Doppler processing was compared. The performance of the LMS algorithm degrades by 3 dB without Doppler processing because of its slow tracking ability. The RLS-based receiver has superior tracking capability and suffers only a 2 dB loss in the absence of Doppler compensation. The reason for the performance loss is illustrated in Fig. 6 where the top panel shows the feedforward tap evolution over time for an uncompensated receiver. Without Doppler compensation the feedforward taps must serve as interpolation filters, adjusting the position of the center tap to track the drift in the equalizer reference point. The filter weights also change with time to match the variation of the dilation or compression. In the lower panel of Fig. 6

the tap weights for the compensated case are shown. Here the center tap stays fixed because the interpolator prior to the feedforward filter provides the time-scale adjustment.

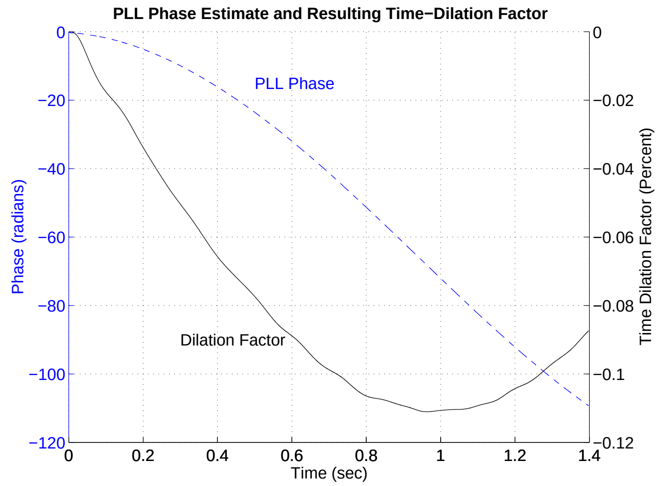

Fig. 5. Phase-locked loop tracking and the corresponding time-dilation factor from a data set with significant source-receiver motion. The Doppler shift is initially zero but soon increases to 9 Hz, corresponding to a relative velocity of 1 m/sec and a time scale change of 0.1%.

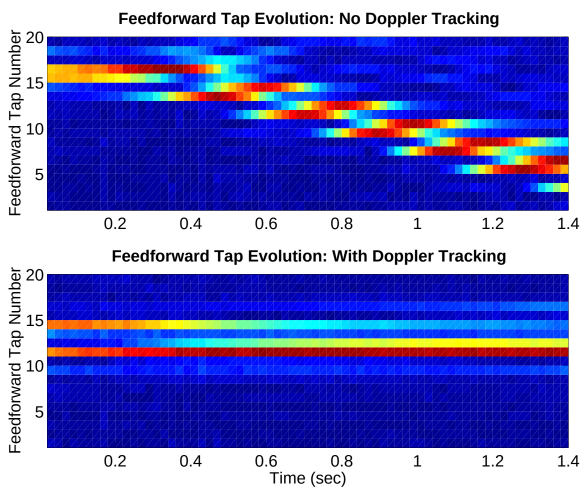

Fig. 6. Feedforward tap magnitude with respect to time for the packet whose phase is shown in Fig. 5. In the uncompensated case the time dilation forces the feedforward filters values to interpolate the signal to the correct sample rate. In the compensated case the interpolation is done by a separate time-varying filter within the equalizer using the interpolation factor derived from the phase estimate. The performance difference is approximately 3 dB.

C. Importance of Transmitter Baffling

The importance of baffling at the transmitter as well as at the receiver is demonstrated by the reverberation visible at 0.13 seconds delay in Fig. 3. This multipath, which is present on both receivers, is generated by energy from the sidelobes of the un-baffled transmitter reflecting from the bottom 100 m below it. The total impact from this low-amplitude diffuse scattering is significant: the mean square-error is increased by about 5 dB as shown in Fig. 7. The constellation without the scattering is shown in Fig. 8. The equalizer output SNR in this case is 27 dB, which will support up to 64-QAM at low error rate [6]. Based on this result, the maximum performance of the acoustic link using both baffled source and receiver and 7.5 W transmit power may be extrapolated to 30,000 bits per second, or 4000 bits per joule at 3000 m.

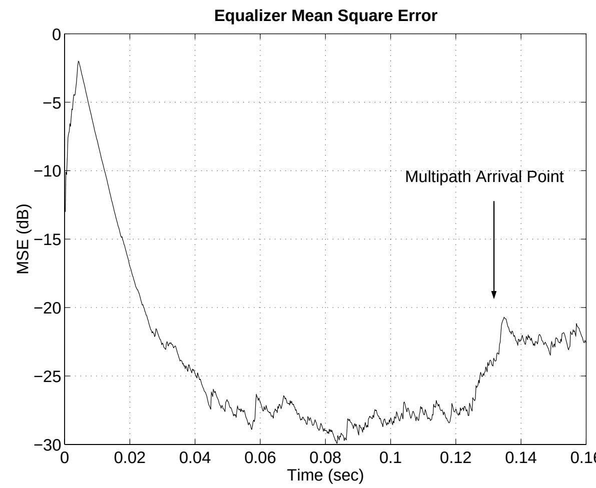

Fig. 7. Equalizer mean-square error showing the best possible equalizer output (about -27 dB after training) as well as the impact of low-amplitude diffuse signals arriving at 0.13 seconds as shown in Fig. 3. This signal is the bottom-bounce from below the transmitter, and even though it is very low amplitude the mean square-error increases by 5 dB, reducing the maximum potential data rate.

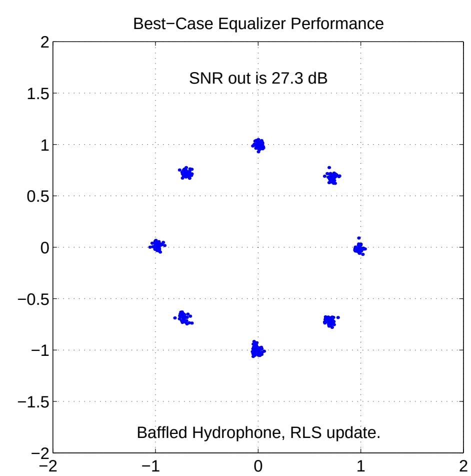

Fig. 8. Equalizer constellation after convergence but before the arrival of the diffuse scattering. This SNR will support up to 64-QAM (30,000 bps) at an error-rate of approximately 10^{-5}.

D. Omnidirectional Receiver Performance

Although baffled, directional receivers provide the immunity from boundary interactions important for a high-performance link, there are a few situations in which omnidirectional receivers may be preferable. In particular, an omnidirectional receiver at the surface could accept data from instruments well away from the base of the mooring. Thus it is instructive to compare directional receiver performance with that achievable using an omnidirectional array.

The SNR at the equalizer output using the two-element omni array is much less than any of the directional receivers due to wave-generated noise and reflected energy from the surface. However, QPSK signaling in conjunction with integrated error-correction (which is necessary in this case to provide low error-rate), allows throughput of 6000 bps with high reliability. The SNR at the equalizer output is 11 dB, and the overall efficiency is reduced to below 1000 bits per joule.

VI. Conclusions and Future Work

High-rate vertical channel communication using a pair of directional transducers was demonstrated at 15000 bps or 2000 bits per joule at a range of 3000 m. Extrapolation using the SNR measured at the equalizer output indicates that this same configuration will operate at up to 30000 bps, yielding an efficiency of 4000 bits per joule. The same transmit-receive combination at 6000 m range will have 6 dB additional spreading loss and 4.5 dB more loss from absorption. Thus the best case SNR of 27.5 dB per symbol as shown in Fig. 8 would be reduced to 17 dB, suitable for 15000 bps 8-PSK, and 2000 bits per joule efficiency at full-ocean depth.

Additional improvements will accrue from tightening the beampatterns of both the source and receiver. A narrower beam provides additional gain but reduces the acceptable watch circle of the surface buoy and requires a tauter mooring. A 30° beampattern (half that used during this test) provides for a 3200 m diameter watch circle in 6000 m water. This beampattern increases the directivity by a factor of two, reducing the amount of power required to achieve the same on-axis source level, thus providing additional link efficiency. A narrower beampattern at the surface reduces the amount of noise integrated by the receiver, further increasing the SNR.

While the multipath experienced over the vertical channel is very simple when compared to long-range horizontal propagation in shallow-water, large source-receiver motions may be experienced on surface platforms and must be tracked and compensated in the receiver. At 1 m/s vertical velocity, the loss without Doppler compensation is 2-3 dB; significantly greater loss would be experienced during high sea states.

In summary, optimization of all elements is key to improving the power efficiency of long-range vertical acoustic communication systems. While the link tested in this experiment offers very good performance, refinement of transducers (paying particular attention to beam patterns and baffling), and continued work to increase the density of the signal constellation, will make the acoustically-linked observatory even more attractive.

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