Basin-Scale Acoustic Communication: A Feasibility Study Using Tomography M-sequences

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Abstract— **Tomography transmissions made over a 3250 km path in the North Pacific as part of the Acoustic Thermometry of Ocean Climate (ATOC) program are analyzed as data communications signals in order to estimate the rate and reliability of very long range undersea telemetry. The ATOC tomography signal is a phase-encoded maximal-length shift-register sequence transmitted at 37.5 symbols per second using a 75 Hz carrier. It may be interpreted as a BPSK data signal at 37.5 bits per second, or as a direct sequence spread spectrum signal with a spreading rate 1023 (the *m*-sequence period) and a resulting data rate of 1 bit every 27 seconds. The multipath arrivals observed at the receiver span nearly 8 seconds, with the majority of the energy occupying the last two seconds. The data are processed using an adaptive multi-channel decision feedback equalizer with integrated phase tracking and Doppler compensation. Equalization of the signal on one hydrophone is sufficient to extract the low-rate spread spectrum modulation, while joint use of all twenty hydrophone channels provides near symbol-rate communications. The excellent results may be attributed to the short term stability (several minutes) of the deep-ocean sound channel at low frequencies.**

I. INTRODUCTION

Undersea acoustic communication at ranges of several hundred to several thousand kilometers will support new civilian and Navy applications of both manned and autonomous underwater systems. While the data rates of long range communications will be low due to bandwidth limitations at frequencies supporting basin-scale propagation, the capability to transmit or receive *any* information will enable control and monitoring of otherwise unreachable instruments or vehicles. Teleoperation of a vehicle in the middle of the North Pacific, or monitoring of ocean-bottom seismometers hundreds of kilometers offshore may become practical. Navy submarines could use such a system for routine or emergency communications at very long ranges when unwilling or unable to surface. A very large scale underwater global positioning system will also require low rate telemetry to convey the subsea equivalent of satellite ephemeris information that is modulated on the GPS timing signal.

Despite the number of potential applications for very low frequency (VLF) acoustic communications, there remain serious obstacles to its actual use. For example, the bandwidth in the frequency range where absorption is low is only several hundred Hertz. Effective use of even this small bandwidth is problematic due to difficulties in low frequency projector design. Broadband sources fielded for tomography experiments are large and typically have low efficiency. An additional issue is the impact of low frequency acoustic communication signals on marine mammals. At a minimum, this issue will necessitate the use of low source levels in certain areas.

Undersea acoustic communications have been an active area of investigation for over twenty years and a tremendous amount of new research and systems development has occurred in the past ten [1]-[3]. Of the many documented communications experiments only a few have been performed at ranges greater than 50 km, and none approaching basin scale. In 1991 Stojanovic, Catipovic and Proakis demonstrated phase-coherent communication at 200 km in deep water in the Pacific using a 1 kHz carrier [4]. Due to source-receiver positions and propagation conditions the multipath spread at 200 km was short, less than 0.1 s, and only 1-5 arrivals were observed at the receiver. The signaling rate was 333 symbols per second and using 8-ary quadrature amplitude modulation (QAM), 1000 b/s was reliably decoded using two hydrophone channels. This is currently the highest rate, longest range communication reported in the literature.

Two experiments at 50 km have been conducted by a European group in the Mediterranean using a 1.7 kHz carrier and signaling rates of 200 and 400 b/s [5] [6]. During these experiments channel spreads of 0.1-0.2 s were observed and several hydrophone channels were required to achieve low error-rate results.

In addition to these experimental results, several authors have suggested specific system designs and predicted the performance of long-range communication systems. In [1], Catipovic presents a notional 1 b/s, 1000-km, 220 Hz design example and points out that while a single ray will have 0 dB SNR per bit at the receiver, accumulation of twenty arrivals may provide 26 dB of gain, provided that they can be coherently processed. In [7], Kwon and Birdsall present *m*-sequence and Gold-code based communications methods suitable for very long-range propagation. This choice of codes is similar to direct-sequence spreading and block-encoding respectively, with the constraint that the code length be longer than the multipath duration.

In the following section, phase-coherent communication is reviewed and additional background on long-range propagation relevant to acoustic communication is presented. In Section III a receiver suitable for spread spectrum and symbol-rate detection is briefly outlined. Section IV reviews the ATOC experiment and the signal, and Section V describes the results of processing the data.

II. LONG-RANGE COMMUNICATION

The design of a very long range acoustic communication system must simultaneously incorporate an understanding of deep-ocean acoustic propagation, signal modulation, and receiver operation. In this section issues related to phase-coherent communication and deep-ocean propagation are discussed.

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A. Phase Coherent Communication

Phase-shift keying offers communication link efficiency by allowing one or more information bits to be transmitted per Hz of occupied bandwidth. While binary phase-shift keying (BPSK) is most commonly used in underwater applications, higher rates are possible using higher-level signal constellations when channel conditions will support them, e.g. the vertical channel [8]. The underwater channel almost always exhibits spread in time and frequency, and thus phase-coherent transmissions normally require some form of adaptive equalization to allow reliable data recovery. The decision feedback equalizer (DFE) described in [4] has been the basis of most phase-coherent receivers proposed to date, though there are numerous variants of the basic form. This receiver provides low bit error-rate performance subject to a number of conditions on both the signal and the transmission channel. Among these are SNR, time variability, Doppler shift and array or diversity gain. The achievable data rate is dependent upon the source level at the transmitter, the number of elements and aperture of the receiver array, and equally important, development of means to remove the effects of very long reverberation times on the communication signals.

In low SNR situations or when the multipath is very complex (either in temporal extent or rate of change) it will become impossible to reliably operate the DFE because the symbols that are fed back to form the error signal are incorrect [4]. Under these conditions the DFE may be modified to allow integrated decoding of the forward error-correcting code within the equalizer. This has been done to support low-SNR conditions or multiple users in the same band [9]. Similarly, direct-sequence spread spectrum signals which use orthogonal or pseudo-noise binary sequences to increase the number of chips per data bit may be adaptively equalized prior to de-spreading to recover processing gain lost during transmission through the channel [10]. This approach is in contrast with most traditional direct sequence spread spectrum systems, where the length of the spreading code is selected to be significantly longer than the channel delay, so that all the multipath is resolved within the duration of one symbol [11].

Use of adaptive processing to remove the inter-symbol interference (ISI) caused by multipath removes one system constraint that limits the information throughput of coding methods such as those described in [7]. Instead, the link performance is limited by the ability of the adaptive processor to compensate for the time-varying channel. If the multipath cannot be removed, then the maximal signaling rate will be proportional to the delay spread which can be two orders of magnitude less than the base symbol rate. The task of the receiver is to equalize the received signal such that symbol-rate communication is possible.

B. Propagation in the Deep Ocean

Modeling and experimental observation of very long-range propagation in the deep ocean has revealed that a signal will spread over 2-8 s as it travels from source to receiver. Acoustic waves traveling at steep angles in the deep ocean traverse faster outside the sound channel and arrive first, while the axial energy (traveling in the sound speed minima) arrives later. The combination of these rays produce a long and complex impulse response with a distribution of energy that builds toward the end [12]. Interaction at the surface and bottom scatters some of the energy, while internal waves in the upper layers of the ocean create fluctuations in the observed signals. These fluctuations add noise to the resolved ray arrivals that tomographers attempt to match against forward model predictions.

While much of the early work in long-range propagation used explosive sources, by the 1970's frequency-modulated sweeps and m-sequences were being considered or in use [12]. Broadband signals require temporal coherence to achieve the desired processing gain, but allow tailoring the spreading in time and frequency to meet source bandwidth constraints and gain goals. Most current ocean acoustic tomography experiments use coherent averaging of multiple periods of an m-sequence to extract the low-level signal.

Around the same time that early acoustic tomography efforts were being proposed (1971), Williams and Battestin published a paper summarizing their attempt to "undistort" a long-range transmission in deep water [13]. During the experiment a 4 s long frequency-modulated sweep was transmitted at 300 Hz over 270 km and 450 km paths south of Bermuda to a 32-element fixed receiver on the ocean bottom. Using a hardware correlator they were able to use the measured impulse response to coherently recombine the multipath to achieve SNR enhancement of approximately 9 dB for the 270 km case and 3 dB for the 450 km case. Two main conclusions were drawn by the authors. First, the coherence time of the multipath at these ranges was at least six seconds, and second, that this time-compression would allow for "symbol resolution time that is much shorter than the multipath spread time" [13]. This result was a clear (and possibly the earliest) demonstration that long range undersea acoustic communication could be performed at symbol rates that are shorter than the delay spread of the channel.

This experimentally-observed stability implies that it should be possible to remove the effects of ocean propagation and potentially allow bandwidth-efficient acoustic communication. However, stability that allows multi-minute averaging for some rays does not necessarily guarantee that all multipath effects can be removed from phase-coherent signals. Interference from dozens of low-amplitude arrivals are certain to reduce receiver performance. However, the irreducible ISI on a single hydrophone may be overcome by combining multiple elements from an array, though the resulting performance is heavily dependent upon array geometry, spatial coherence and the dispersion of the acoustic channel. Thus the challenge is to design a signaling methodology and a receiver which will take advantage of the available channel stability and large-aperture arrays in order to maximize SNR at the receiver output.

III. THE RECEIVER

The approach proposed for the receiver is a combination of adaptive equalization and coherent combining similar to that of [4], but with the addition of integrated Doppler processing and error-correction or de-spreading. The receiver with Doppler processing is shown in Fig. 1. The receiver operates on n channels of the complex demodulated data sampled at twice the symbol rate. The data is first passed through a time-varying resampling filter that adjusts the time scale of the signal to compensate for the Doppler effects. The time scale measure is driven by the estimate of carrier phase $\hat{\theta}$ obtained from the phase-locked loop (PLL). The Doppler subsystem may be initialized with an externally-obtained estimate of the carrier frequency offset ω_0 if it is available, though the second-order PLL will lock onto the carrier phase during the equalizer training period without any prior estimate.

The data interpolated by the Doppler processor then passes through n feedforward filters prior to being combined with the output of the feedback filter. This signal is phase-corrected using the PLL output θ to form $\hat{d}$, the soft estimate of the current symbol. The symbol is quantized to generate a hard decision $\tilde{d}$ which is used to create an error signal. The error signal drives the adaptation of the feedforward and feedback filters which are computed using the least mean square (LMS) or recursive least square (RLS) algorithms. Integrated block error-correction or despreading (for the spread spectrum case) is performed every L symbols, where L is the block or spreading code size. This process is described more fully in [9] and [10].

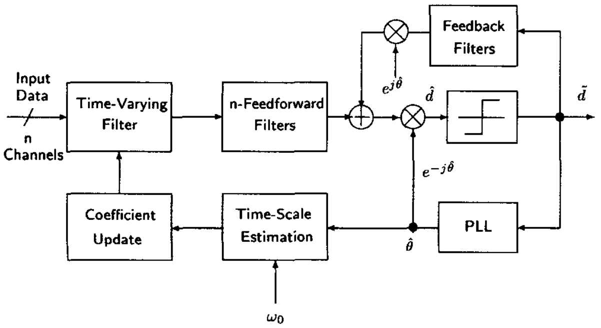

Fig. 1. Multi-channel decision feedback equalizer with integrated Doppler estimation and compensation.

IV. EXPERIMENT DESCRIPTION

The ATOC Acoustic Engineering Test was performed in November 1994 in the North Pacific Ocean. The test has been completely documented in [14], but the main parameters are summarized here. The source was deployed in the sound channel at 600 m using R/P Flip which was held in a three-point mooring off Southern California. The receiver was a 20-element, 700 m vertical line array located 3200 km away near the Hawaiian Islands. The water at the source was 4000 m deep, while at the receiver it was over 5000 m. The source level was 195 dB.

The phase-modulated m-sequence transmitted from the ATOC source at 75 Hz carrier utilizes 37.5 Hz of bandwidth. Thus each digit (or "chip," in spread spectrum terminology) of the sequence is two cycles of the 75 Hz carrier. The sequence length L is 1023, and thus the period of the sequence is 27.28 s. The number of periods transmitted was 20, 40, or 80 corresponding to approximately 10, 20 or 40 minutes. The transmissions were sent at two or four hour intervals over seven days [14].

The binary m-sequence can be interpreted as a BPSK communication signal with an information rate of 37.5 bits per second. Alternatively, it is analogous to a direct-sequence spread spectrum signal where each 1023 chip sequence is multiplied by $[-1, 1]$ representing a single information bit $[0, 1]$. In this case, the 40 data bits corresponding to the 40 periods are all 1. It should be noted that modulating the m-sequence destroys the periodic autocorrelation function desired for tomography. However, *not* modulating the sequence has no impact on our ability to interpret it as a communication signal.

The data are bandpass filtered and sampled at 300 Hz for future analysis. Prior to communications processing the raw data were complex demodulated to baseband at two samples per symbol, or 75 Hz. Coarse synchronization of the start time was accomplished by correlating with one period of the m-sequence. In the analysis that follows, one 40-period data set taken on year day 321 is examined.

V. RESULTS

The equalizer of Fig. 1 is used to process 1, 10 and 20 hydrophone channels. The length of the equalizer feedforward filters are chosen to span the dominant energy toward the end of the arrival as shown in the top panel of Fig. 2. The number of fractionally-spaced taps is selected to be 180, which is 90 symbols (1.2 s). While this encompasses only a portion of the arrivals, it includes a significant amount of the total energy. It is interesting to note that while ocean tomography generally uses the early, identifiable rays rather than the late arrivals, most of the energy is actually in the later group. In contrast, the communications receiver focuses on the late portion of the arrival pattern to maximize energy retrieval. The number of feedback taps in the equalizer is set to 60, so for the single channel case the total number of parameters is 240. The 10 and 20 channel cases use 1860 and 3660 parameters respectively. This number of parameters is too large for the RLS algorithm and so the LMS algorithm with adaptive step-size is used. Convergence of this large system takes on the order of several thousand symbols.

The channel impulse response without adaptive equalization is shown in the top panel of Fig. 2. The effectiveness of the processor can be observed directly by correlating the equalized symbol estimates $\hat{d}$ with the transmitted sequence. Perfect equalization would produce a delta function after correlation with the transmitted signal. Single channel equalization (Fig. 2, middle panel) removes a significant amount of ISI, though sufficient residual ISI is present to preclude symbol-rate communication. However, interpreting the output as a 1023 chip-per-data-bit spread-spectrum signal yields very high output SNR. Adaptively equalizing 10 or more hydrophone channels provides an impulse-like output with almost no ISI after correlating with the transmitted signal

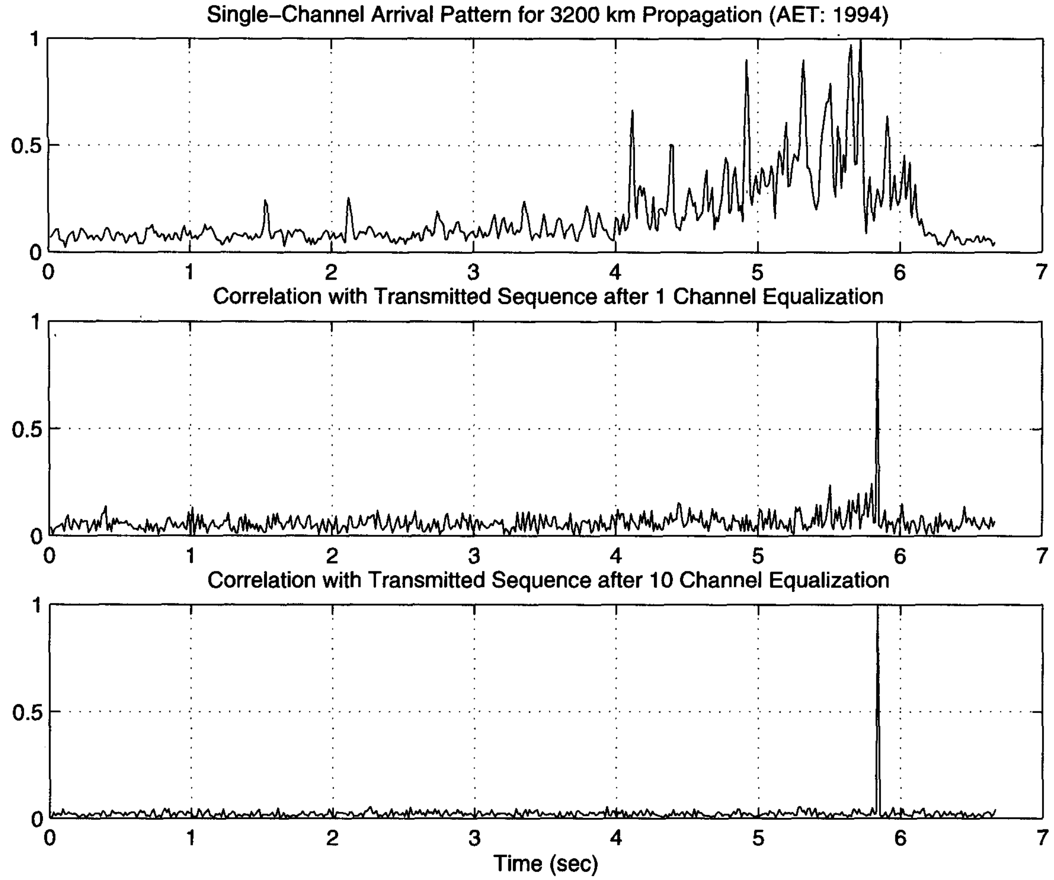

Fig. 2. Demonstration of single and multi-channel coherent processing applied to ATOC m-sequence signals after propagating 3200 km in the Pacific. Top: impulse response obtained by correlating the received signal with the m-sequence. Middle: result of correlating after adaptively equalizing one hydrophone channel. Bottom: correlation result after 10 channel equalization.

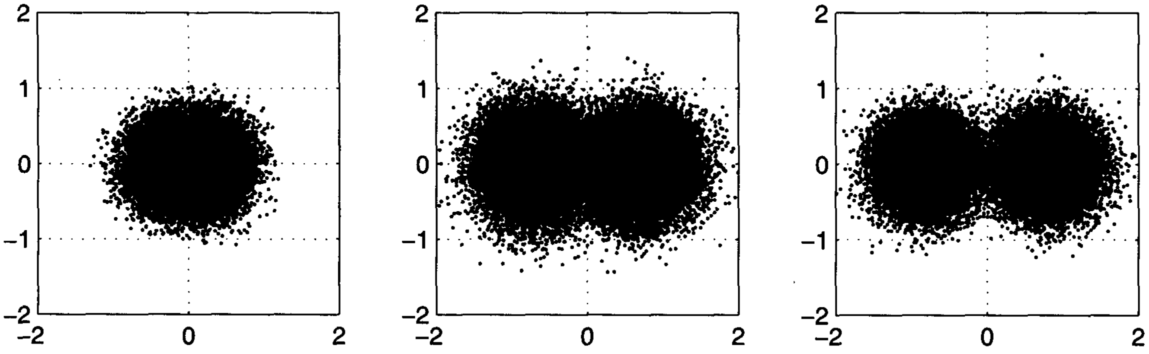

Fig. 3. Symbol-rate constellation plots for 1, 10 and 20 channel equalization.

(Fig. 2, bottom panel).

In Fig. 3 the constellation plots from single, 10 and 20 channel processing are shown in order to allow observation of symbol-level fidelity. The output SNR for the 10 channel case is 4.6 dB, while for the 20 channel case it is 6.3 dB. The output SNR for 10 and 20 channels demonstrates that symbol-rate communication *is* possible. This remarkably good SNR is achieved despite the very long time dispersion. It should be noted that the resulting data rate for this example would be slightly less than 37 bits per second when error-correction coding is added.

It should be noted that this data rate is likely to be at the high end of what is feasible for a practical basin-scale system due to the optimal placement of the source and receiver in the sound channel. In addition, the receiver is exploiting the spatial diversity available from the 700 m long vertical array.

The phase estimated by the integrated PLL is shown in Fig. 4 for two of the cases discussed above. A 300 s periodicity may be observed in the time-domain plot. Some higher frequency energy is present as shown in the power spectrum (Fig. 5), but physical causes are not easy to infer. Additional work is required to ascertain whether or not any of the information provided by the adaptive equalization process is meaningful to long-range propagation analysis.

VI. CONCLUSION

Signals transmitted by the ATOC Consortium over a 3250 km path in the North Pacific Ocean have demonstrated stability that allows coherent averaging for many minutes. This stability is exploited using a multichannel adaptive equalizer which allows direct-sequence spreading or error-correction code selection to be unconstrained by the delay spread of the channel. The excellent performance of the receiver should not necessarily be a surprise, given that multiple minutes of m-sequence are coherently combined using standard pulse compression techniques to provide processing gain for acoustic tomography measurements. These results further reinforce the conclusion that basin-scale VLF propagation is amenable to coherent processing [15][16].

A number of other receiver architectures may also be considered. For example, time reversal of the data stream to change it from non-causal to causal may improve performance. Channel estimation-based receivers [17] may also improve the tracking performance that suffers when the equalizer filters are as large as described here. In addition to recovery of the transmitted information, these methods provide an estimate of the multipath structure.

The design of a permanent system capable of the performance described here will be done most effectively in conjunction with future tomography and ocean acoustic monitoring programs. Engineering issues associated with deployment of large vertical arrays coupled to surface links or cabled to shore are not trivial, but they have proven to be surmountable. While the Navy Sound and Surveillance (SOSUS) arrays may be useful as long-range data receivers [18], the fact that they are located on the bottom means that less energy may be available, and thus the data rate per horizontal array may be lower than for a similar vertical array. Analysis of raw data from the SOSUS stations and development of a methodology for combining data from multiple widely-separated arrays is still required. However, a SOSUS-based receiver system is conceptually attractive and similar to the deep space network, which uses many high-gain antennas located around the world to collect low-power signals from remote space craft.

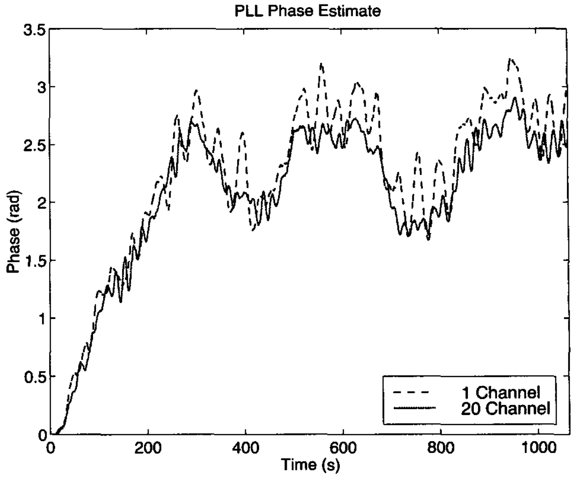

Fig. 4. Phase estimate from the phase-locked loop for the 1 and 20 channel equalization cases.

The best set of acoustic receivers for future civilian science applications would take advantage of arrays wired into the NEPTUNE fiber-optic undersea network [20] or utilize components of the proposed semi-permanent deep ocean observing system (DEOS) [19]. The arrays can be placed to span the water column in order to maximize the retrieval of transmitted energy, thus reducing the required source level to save power and minimize potential environmental impact. Another important factor in the design of a basin-scale acoustic receiver is placement of receivers to minimize shipping noise. Areas near major shipping lanes in the North Pacific have significantly higher noise than the South Pacific or south-west of Hawaii where the ATOC array was located.

In summary, the ATOC acoustic engineering test was designed to measure acoustic travel time over a 3000 km path in order to study temperature and interior ocean processes. While the experiment was conceived without basin-scale data telemetry as a test component, it provided exactly the information required to demonstrate its feasibility.

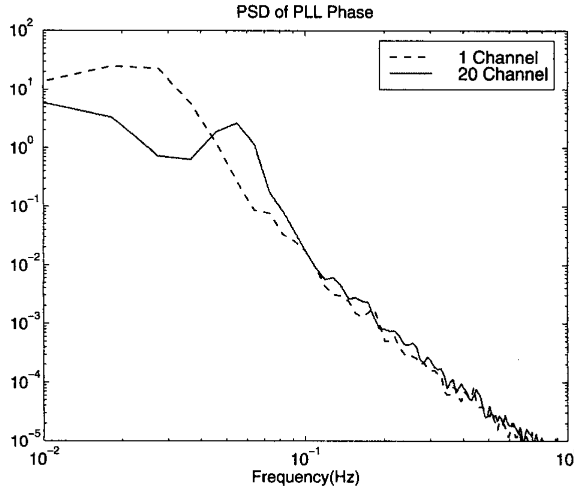

Fig. 5. Spectrum of the phase estimate from the phase-locked loop for the 1 and 20 channel equalization cases.

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REFERENCES

[1] J. Catipovic, "Performance limitations in underwater acoustic telemetry," *IEEE J. Oceanic Eng.*, vol. 15, no. 3, pp. 205-216, July, 1990.
[2] M. Stojanovic, "Recent advances in high-speed underwater acoustic communication," *IEEE J. Oceanic Eng.*, vol. 21, pp. 125-136, 1996.
[3] D. B. Kilfoyle and A. B. Baggeroer, "The state of the art in underwater acoustic telemetry," *IEEE J. Oceanic Eng.*, vol. 25, no. 1, pp. 4-27, 2000.
[4] M. Stojanovic, J. A. Catipovic and J. G. Proakis, "Adaptive multichannel combining and equalization for underwater acoustic communications," *J. Acoust. Soc. Amer.*, vol. 94, no. 3, pt. 1, pp. 1621-1631, Sept. 1993.
[5] V. Capellano, "Performance improvements of a 50 km acoustic transmission through adaptive equalization and spatial diversity," *Proc. Oceans 1997*, Halifax, Nova Scotia, 1997.
[6] A. Plaisant, "Long range acoustic communications," *Proc. Oceans 1998*, Nice, France, 1998.
[7] H. M. Kwon and T. G. Birdsall, "Digital waveform codings for ocean acoustic telemetry," *IEEE J. Oceanic Eng.*, vol. 16, no.1, pp. 56-65. Jan. 1991.
[8] L. Freitag, M. Johnson and D. Frye, "High-Rate Acoustic communications for Ocean Observatories: Performance Testing Over a 3000 m Vertical Path," Proc. Oceans 2000, Providence, RI, Vol. 2, pp. 1443-1448, September 2000.
[9] M. Stojanovic and L. Freitag, "Multiuser undersea acoustic communications in the presence of multipath propagation," *Proc. Oceans 2001*, Honolulu, Nov. 2001.
[10] M. Stojanovic and L. Freitag, "Hypothesis-feedback equalization for direct-sequence spread-spectrum underwater communications," *Proc. Oceans 2000*, Providence, RI, Vol. 1, pp. 123-128, September 2000.
[11] R. L. Peterson, R. E. Ziemer and D. E. Borth, *Introduction to Spread-Spectrum Systems.* NJ: Prentice Hall, 1995.
[12] W. Munk, P. Worcester and C. Wunsch, *Ocean Acoustic Tomography*, Cambridge: Cambridge University Press, 1995.
[13] R. E. Williams and H. F. Battestin, "Coherent recombination of acoustic multipath signals propagated in the deep ocean," *J. Acoust. Soc. Amer.*, vol. 50, no. 6, pt. 1, pp. 1433-1442, Dec. 1971.
[14] P. F. Worcester et. al., "A test of basin-scale acoustic thermometry using a large-aperture vertical array at 3250-km range in the eastern North Pacific Ocean," *J. Acoust. Soc. Amer.*, vol. 105, no. 6, pp. 3185-3201, June 1999.
[15] J. Colosi et. al., "Comparisons of measured and predicted acoustic fluctuations for a 3250-km propagation experiment in the eastern North Pacific Ocean," *J. Acoust. Soc. Amer.*, vol. 105, no. 6, pp. 3202-3218, June 1999.
[16] J. Colosi and the ATOC Group, "A review of recent results on Ocean acoustic wave propagation in random media: basin scales," *IEEE J. Oceanic Eng.*, vol. 24, no. 2, pp 138-155, April, 1999.
[17] M. Stojanovic, L. Freitag, and M. Johnson, "Channel-estimation-based adaptive equalization of underwater acoustic signals," *Proc. Oceans 99*, Seattle, Washington, 1999.
[18] B. D. Dushaw, B. M. Howe, J. A. Mercer, R. C. Spindel, and the ATOC Group, 'Multimegameter-range acoustic data obtained by bottom-mounted hydrophone arrays for measurement of ocean temperature," *IEEE J. Oceanic Eng.*, vol. 24, no. 2, pp. 202-214, April, 1999.
[19] "Illuminating the hidden planet: The future of seafloor observatory science," National Academy of Sciences/National Research Council, July 2000.
[20] NEPTUNE Feasibility Study, www.neptune.washington.edu.