Underwater Acoustic Communications for Bottom-Mounted Sensor Networks

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Introduction: The U.S. Navy's SEA POWER 21 FORCEnet vision demands the development of undersea sensing systems that can provide the warfighter with accurate and rapid awareness of the battlespace environment. To this end, undersea sensor networks in shallow water environments will be required to act as defensive fields and barriers in the protection of American shores, Navy assets, and sea bases.[1] The Deployable Autonomous Distributed System (DADS) is such a network, tailored for the purpose of antisubmarine warfare (ASW). Equipped with acoustic and electromagnetic sensors coupled to robust data fusion schemes, DADS automates the reduction of sensor data to useful information, thereby greatly assisting decision-making personnel to ensure that enemy submersibles are kept at a distance from friendly forces.[2]

In support of underwater sensor networks, the Naval Research Laboratory is developing accurate communication receiver algorithms for the high-frequency, shallow-water acoustic channel. These algorithms support phase coherent communications and are suitable for long-endurance battery-powered systems. Reported here is a channel estimation based decision directed (CE-DD) algorithm for the demodulation of acoustic transmissions between bottom-mounted sensors. This algorithm has been tested on high-frequency experimental data collected recently in St. Margaret's Bay, Nova Scotia, during the 2006 Underwater Networking (Unet06) experiment and in the Gulf of Mexico, Florida, during AUVFest/Unet07 demonstrations. These tests were conducted in collaboration with Defense Research Development Canada (DRDC) as part of The Technical Cooperation Program (TTCP) Maritime Systems Group Technical Panel 9 (MAR TP-9) sanctioned efforts. The results demonstrate that allowable rates are fundamentally linked to environmental conditions such as surface conditions, water depth, sound speed profile, and seabed properties.

Reduced Computation Channel Estimation Based Receiver Algorithm: The NRL-developed algorithm is based on a block coherent approximation of the acoustic response function and achieves computational reductions by approximating matrix inversions with conjugate gradient iterations.[3] This approach offers computationally scaleable processing, providing a more judicious focus of computational resources.[4] Figure 1 is a simplified block diagram of the CE-DD algorithm for bottom-mounted, limited-aperture applications. The algorithm's adaptive filtering computations maximally exploit FFT computational methods to solve the block Toeplitz system associated with approximating a time-varying channel as coherent over short finite duration blocks.

Performance of the CE-DD Algorithm: The algorithm has been tested on ocean acoustic data sets at 44 kHz center frequency in signaling experiments associated with TTCP-MAR TP-9 sanctioned undersea networking demonstrations. The Unet06 experiment took place in St. Margaret's Bay in June 2006 in 70 m of water. The sound speed profile was downward refracting and the sediment bottom was soft and silty. The Unet07 experiment took place in June 2007 at Panama City, Florida, in the Gulf of Mexico in 20 m of water exhibiting very close to isovelocity sound speed; the bottom was sandy. In both experiments the sea surface was quite dynamic with significant wave height greater than 1 m. Figure 2 gives a representative picture of the performance of the algorithm at approximately 600 m range with 6-phone reception in St. Margaret's Bay and at 400 m range with 8-phone reception in the Gulf of Mexico. In both cases SNR was over 15 dB. The significant impact of water depth, sound speed, and sea floor

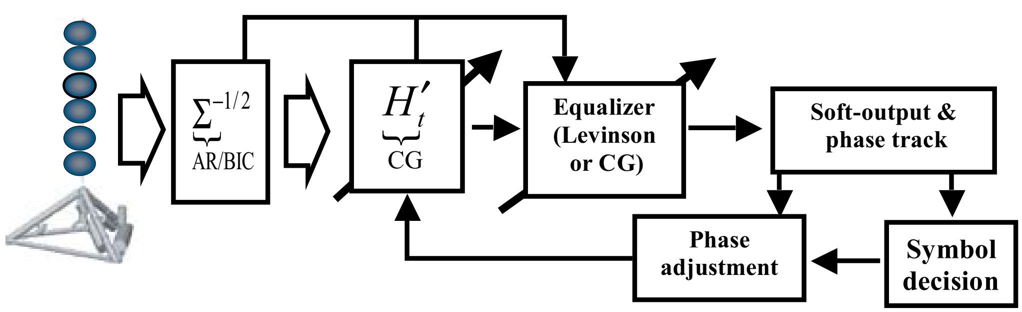

FIGURE 1
CE-DD algorithm. An equalizer on the single channel is constructed from the noise statistics and the estimated channel response functions across the array. The equalized stream is then used to make symbol and motion induced phase correction estimates.

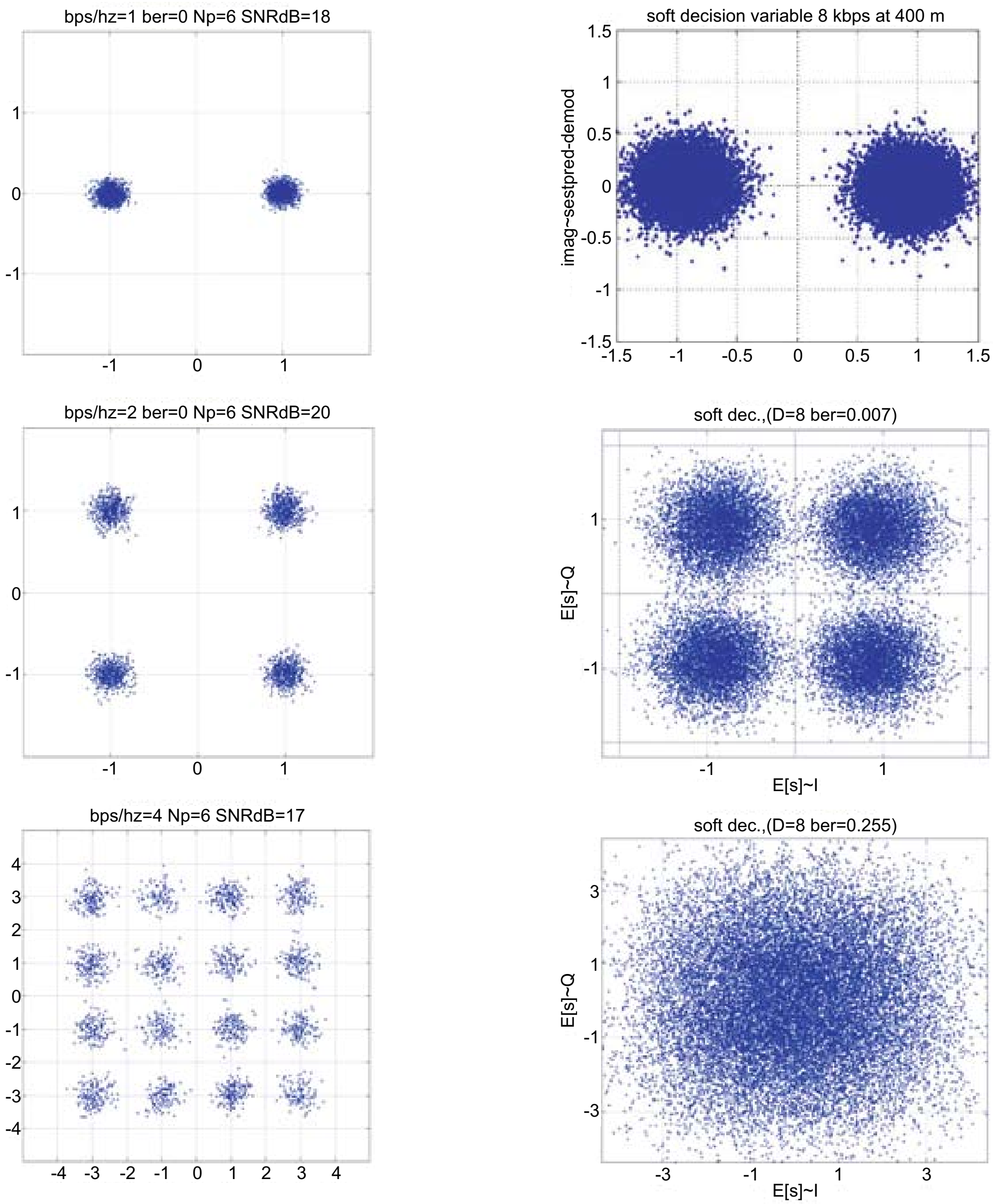

FIGURE 2
Performance of the CE-DD algorithm in terms of estimated output constellation scatter plots. To the left, St. Margaret's Bay environment at 44 kHz and approximately 600 m range. To the right, Gulf of Mexico environment at approximately 400 m range. Bit densities range from 1 bps/Hz (bpsk) to 4 bps/Hz. The algorithm can support 4 bps/Hz in the downward refracting sound speed with the soft bottom of St. Margaret's Bay. Surface conditions at the two sites were similar.

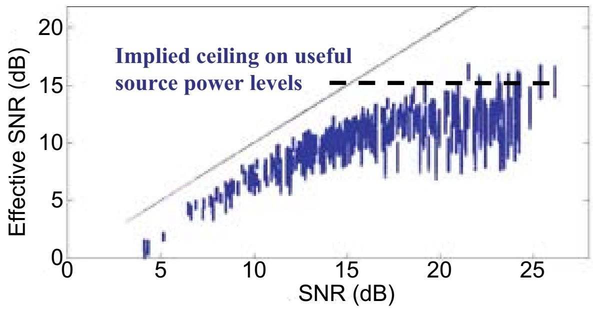

FIGURE 3
Effective SNR, incorporating the self-noise associated with channel estimation variance, as a function of SNR aggregated over all 8 (1.8 m aperture) hydrophones for the 44 kHz St. Margaret's Bay acoustic communications experiment. It is noticed that there is a ceiling on useful power levels of approximately 17 dB.

properties presents a stark contrast between these two environments when surface conditions are similar. It is demonstrated that 1.8 meters of aperture can support 4 bps/Hz signaling quite well in the more benign St. Margaret's Bay where acoustic paths are naturally refracted away from the dynamic surface. Such rates are unsupportable in the harder bottom isovelocity channel of the Gulf of Mexico. The 2 bps/Hz transmission represents a 16 kbps communication rate and at 600 m corresponds to over 8 kbps-km. Likewise the 4 bps/Hz represent a 16 kbps-km throughput.

Effects of Limited Channel Temporal Coherence: Figure 3 summarizes the impact of channel estimation errors for St. Margaret's Bay in terms of an effective signal-to-noise ratio. The effective signal-to-noise ratio combines the ambient whitened acoustic noise power with a self-noise that scales with both channel estimation variance and acoustic power for the source signal itself.[5] This statistic helps quantify the impact of environmental factors on receiver performance. The effective signal-to-noise ratio provides a measure of the maximum useful source levels for a given environment. In this case it is clear that signaling with received levels above 17 dB leads to no net improvement in performance and should be avoided.

Summary: The Naval Research Laboratory has developed adaptive filtering methods in support of high-rate high-frequency underwater acoustic communications for bottom-mounted sensors. These methods are accurate and are amenable to scaleable computational schemes.[4] These algorithms have been tested in at-sea conditions from bottom-mounted configurations supporting data rates up to 4 bps/Hz at ranges of up to 1 km at received SNRs of 17 dB in suitable environments.[5] These methods are being advanced for use in bottom-mounted sensor networks that must operate on a limited power budget in diverse shallow water environments that exhibit a range of multipath spread and path-dependent temporal coherence.[4]

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