Toward continuous underwater acoustic communications

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***Abstract* - The paper addresses the technical challenges and approaches for semi-continuous underwater acoustic communications, i.e., transmission of long packets under different environmental conditions without periodic training. The packet length is normally constrained by the channel coherence time for a given bandwidth, beyond which channel tracking using an adaptive decision feedback equalizer becomes difficult. But if the channel is known for each block of coherence time, communications can proceed in principle continuously without time limitation. Using the iterative correlation-based equalizer where decision symbols are assumed to be the true symbols to estimate the channel condition, it is shown based on at-sea data that long packets of data can be transmitted with minimal errors even in harsh environments where the channel coherence time is very short (a fraction of the packet length).**

I. INTRODUCTION

Underwater acoustic communications (ACOMMS) are useful for many practical applications. For example, they enable wireless data telemetry from a distributed field of remote sensors for the purpose of environmental monitoring, provide wireless command and control to remotely operated autonomous underwater vehicle (AUV). For such applications, the benefits of ACOMMS include: easy deployment of remote sensors without the constraints of cables; flexibility in maneuver of an underwater vehicle without a tether; and the affordability when operating in a wide area underwater (acoustic) network. The remotely operated vehicle (ROV), made famous during the exploration of the Titanic ship wreck, sent many underwater video images continuously to the mother ship. It seems desirable to be able to one day transmit video images using ACOMMS, thus avoiding the use of a tether. Continuous transmission of images requires continuous or semi-continuous ACOMMS.

Compared with a cabled system, such as a ROV, the obvious drawback of using ACOMMS is its limited data rate due to the finite bandwidth available in an underwater acoustic channel. Because of the limited bandwidth, the communication technique must use the bandwidth efficiently. Bandwidth efficient communications generally require phase coherent modulations. Examples are quadrature phase-shift-keying (QPSK), which yields a (per Hz) data rate of 2 bits/sec/Hz respectively. For a bandwidth of 20 kHz, one obtains a (total) data rate of 40 kbits/sec, which makes transmission of compressed video images from an underwater remote camera possible [1]. Currently, ACOMMS using the multichannel decision feedback equalizer (DFE) receiver algorithm use packets of approximately 5-10 thousands of symbols [1]. Multiple packets would be required to transmit a large amount of data, such as a video image [1]. For each packet, a probe signal is placed at the beginning of the packet, followed by a guard time, for the purpose of estimating the channel impulse response (CIR) and symbol synchronization. Training data are needed for the equalizer to learn the channel. Together with the probe signal, they can consume 10-30% of resources. When multiple packets are transmitted, the packets need to be well separated in time to avoid interference between packets. Thus, while the burst data rate is high, the average data transmission rate (throughput rate) is not.

Given a limited bandwidth, one way to improve the data rate is to increase the symbol constellation size, such as 8PSK, which is possible in a vertical channel and certain time-invariant horizontal channels, but usually difficult in a time-varying horizontal channel. The other way to improve the data transmission rate is to minimize the packet overhead, and the gaps between packets, i.e., by maintaining semi-continuous transmissions using long packets. To transmit and receive long duration packets, the receiver algorithm must be able to track and compensate the channel time variation, and maintain the performance of the DFE beyond the channel coherence time. In other words, the communications must not be interrupted by changes in the environmental conditions.

For an operational system, the ACOMMS need to work autonomously under different environmental conditions and maintain consistent performance as source and receiver change range and depth, assuming that the received data has a sufficient signal-to-noise ratio. The environmental conditions change from oceans to oceans, since different oceans have different sound speed profiles and different bottoms, resulting in different multipath arrival patterns. In many oceans, eddies, internal waves, turbulence, and rough sea surface can cause the propagation condition to change significantly over a short period of time. In addition, there are some practical constraints for an operation system. A practical system usually has a limited processing power. A single source transducer and a small number of receivers are envisioned

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for the communication system in the near future. The robustness requirements and practical constraints need to be considered in developing the transmitter/ receiver (algorithm) design for a practical system.

II. ITERATIVE CORRLEATION-BASED EQUALIZER

A method for semi-continuous ACOMMS is presented in this paper. It is based on the correlation-based equalizer (CBE) which has been shown to be applicable to environments with different sound speed profiles using a fixed set of parameters [2], thus avoiding the need of (frequent) parameter adjustments due to changes in the environmental conditions. It has been tested with at-sea data over many oceans and its performance is insensitive of the source-receiver range and depths.

The CBE works by estimating the channel impulse response and applying passive-phase conjugation (PPC) to the received data, followed by a single-channel DFE. The DFE works up to the channel coherence time during which the channel can be assumed quasi-stationary. To communicate beyond the channel coherence time, one needs to re-estimate the channel based on the decision data [3]. To generalize this method to a (rapidly) varying environment, the data are divided into blocks, each with a length or the order or less than the channel coherence time. The CIR estimated from the previous block is used to estimate the symbols of the current block via the CBE method. The decision symbols so obtained are used with the current block of data to re-estimate the channel impulse response. The newly estimated channel impulse response is re-applied to the data to re-estimate the symbols using a next round of CBE; this process can continue iteratively. In practice, one iteration (two CBEs) is often sufficient. The method is referred to as an iterative correlation based equalizer (ICBE). A schematic diagram of the processor is shown in Fig. 1.

The method requires a rough estimate of the channel coherence time to set the block size, which can be either estimated in situ using channel probe signals or determined from the data base (from previous measurements). Figure 2 shows the temporal coherence time, $\tau_{0.8}$ (the time lapse for the temporal coherence to drop to 0.8), over many oceans [4], where the (iterative) correlation-based equalizer has been tested.

III. EXPERIMENTAL RESULTS

The ICBE method was tested during the 2007 autonomous underwater vehicle festival (AUVFest 07), which took place in June, 2007 in water south of the Panama City, Florida. The data analyzed were collected in water of 20 m depth. The channel properties are summarized in Table I. Selective packets were processed during the AUVFest 07 experiments and reported at the end of the experiment. More data were processed in post-experiment analysis and reported during the AUVSI Unmanned Maritime System Technology symposium [5].

During times when the sea surface was relatively calm (sea state ~ 0), the channel varied slowly with time. The impulse responses measured over a period of 30 min is shown in Fig. 3a. The multipath spread (at -15 dB level) is ~ 5 ms. Approximately 60 packets, transmitted over a period of 30 min, were analyzed. Each packet is about 25 sec long, containing ~102K symbols. Since the channel coherence time is longer than 25 sec (Fig. 2), the data were processed by treating the entire packet as one block. One finds that all 60 packets yield an uncoded bit error rate (BER) < 1% with two receivers. Some packets can be processed with one receiver with BER ~ 1.5%. BER as a function of the number of receivers is shown in Fig. 5a.

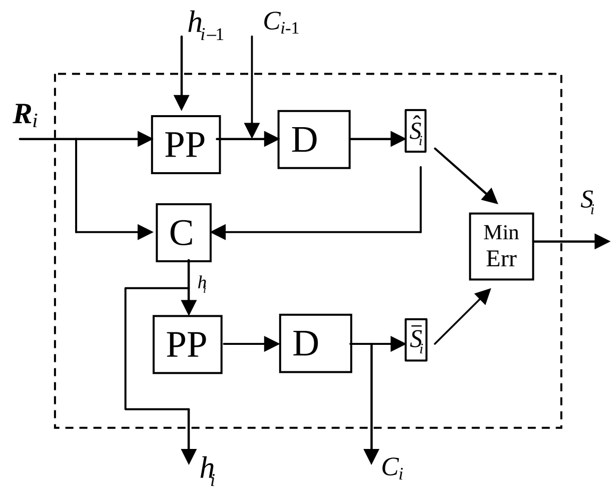

Figure 1. The schematics of the ICBE algorithm. PP stands for passive-phase conjugation, D stands for single channel DFE, and C stands for channel estimation (CE). The algorithm is symbolically represented as $(PPC+DFE)^2+CE$.

During times when the sea surface is rough (sea state ~ 3), the multipath spread (at -15 db level) increases to 20 ms, due to extended scattering of sound from the rough sea surface (see Fig. 3b). The channel coherence time shortens significantly to $\tau_{0.8}$ ~ 0.1 sec. The (25 sec long) packets were processed using ICBE with a block size of 500 symbols (~ 0.1 sec). Figure 4a shows that the multipaths exhibit rapid fading with time on an individual channel. In contrast to the data analyzed earlier during calm sea conditions, where data can be equalized often with a single receiver, the rough sea data requires spatial diversity to combat signal fading. Figure 4b shows the BER as a function of the number of receivers. Five receivers are needed to achieve < 1% BER for a duration of 25 seconds.

We have also evaluated the ICBE methods for the purpose of transmitting long packets in shallow water of depth 60-70 m. One set of data was collected in an enclosed bay (the St. Margaret's bay, outside of Halifax, Canada) in June of 2006 as part of the Underwater Networking (UNet) experiment. The other set of data was collected during the Time Reversal Experiment (TREX) in

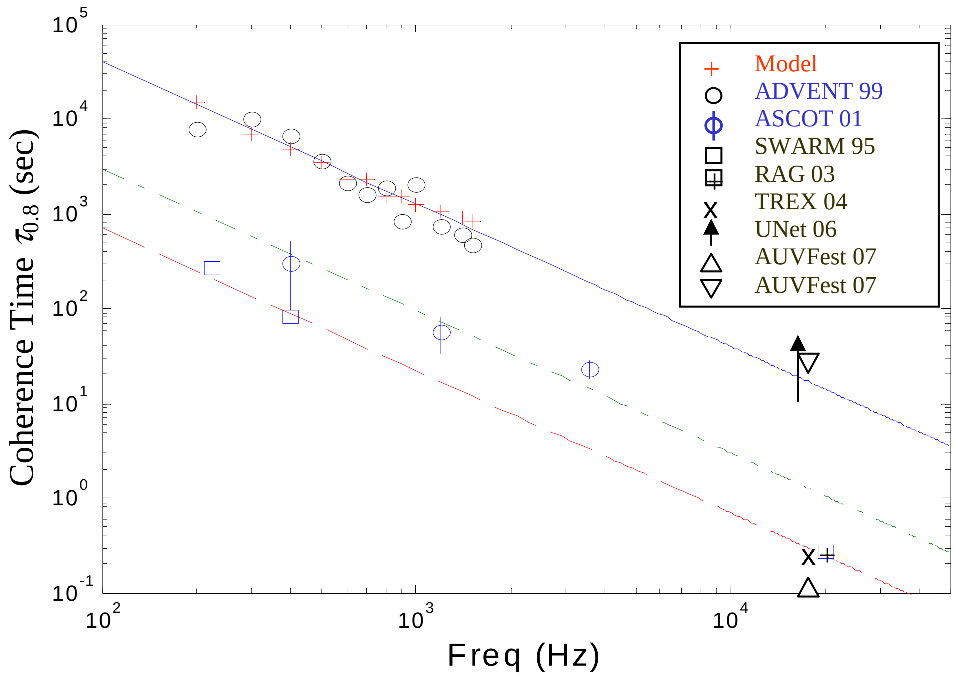

Figure 2. Signal coherence time measured over various oceans: ADVENT experiment is over the Adventure Bank in the Mediterranean; ASCOT experiment took place on the New England Shelf; SWARM, RAG and TREX experiments were done off the coast of New Jersey; UNet 06 experiment took place in the St. Margaret's Bay, out of the Halifax, Canada; and the AUVFest experiment was in water south of Panama City, Florida.

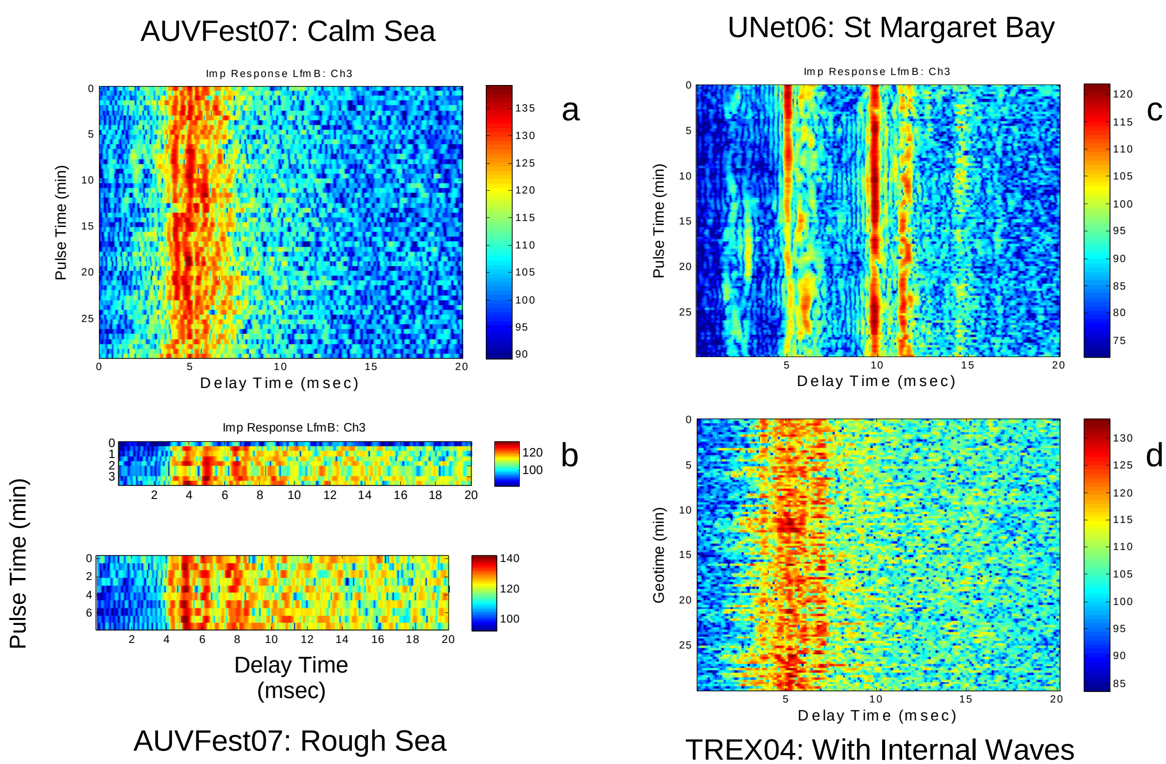

Figure 3. Channel impulse response measured during the various experiments: the inter-packet channel variation.

April 2004, off the coast of New Jersey, southwest of the Hudson Canyon. The sound speed profile was downward reflective in both places. Except for intrusion of fresh water, the St. Margaret bay is relatively simple oceanographically speaking. The New Jersey Shelf is known to have internal waves and turbulences. It provides a highly dynamic environment. The channel properties are also summarized in Table I. Again, the main difference between the two environments is the relatively long coherence time in the enclosed bay environment and relatively short coherence time in the open ocean environment. For the UNet06 data, the entire packet was processed as one block, but for the TREX04 data, one must use a small block size of 500 or 1000 symbols (~0.2 sec) as channel is rapidly changing. Similar performance is obtained as in the AUVFest rough sea case. For both cases, five receivers are needed to achieve a minimal bit error rate (See Fig. 5b and 5d). Multiple receivers are needed to counter signal fading (see Fig. 4a).

IV. DISCUSSIONS

The ICBE is implemented by processing two blocks at a time, to be repeated block after block; each block is processed twice. For each block, CIR is updated, and is used via PPC to produce an equivalent channel whose CIR is the auto-correlation function of the individual receiver channels summed over all channels, i.e., the so called Q function [2]. One finds that the Q function with channel re-estimation has a high coherence ($\geq$ 0.9) across the blocks (result not shown here). Stated differently, the correlation channel has a long coherence time greater than packet length (10-25 s). It is well known that DFE works well in a highly coherence channel; in this case it is relatively straightforward for the DFE to proceed from block to block. In contrast, the original channel has a very short coherence time (< 0.2 s). In that case, the DFE has to track all the changes in the channel which is difficult when the channel is varying rapidly. This is the one of the reasons that ICBE can in principle communicate over a period of time much longer than the multichannel DFE.

It is noted that for a time invariant channel, the ICBE (or CBE in this case) has identical performance as the multichannel DFE (at least in theory). For a rapidly changing channel, the ICBE presents an advantage because it assumes (prior) knowledge of the (average) CIR for each block, which it obtains, in practice, from DD-CE, based on the assumption that decision symbols are correct. This prior information is equivalent to having periodic training symbols for the multichannel DFE.

V. SUMMARY

Data collected in three experiments, under four different environmental conditions are analyzed in this paper to evaluate the prospect of semi-continuous underwater acoustic communication at high (> 10 kHz) frequencies (for the purpose of transmitting video images). For the benign environments, such as calm sea or enclosed bay, the channel coherence time is relatively long, one can process data using a large block at a time. Often a small number of receivers (e.g., 2) will be sufficient. For the tough environments, such as rough seas, or in open oceans with internal waves, the channel coherence is relatively short, and one must use a small block size with frequency channel estimation in order to transmit long duration packets. Multiple receivers (e.g., 5) are required due to rapid fading of the multipath arrivals. This paper shows for the first time persistent performance of underwater acoustic communications using long duration packets (10-25 sec) containing > 40-102 K symbols. The results suggest that high data-rate phase-coherent semi-continuous underwater acoustic communications may one day be possible to transmit video images from underwater sites.

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Table I. Measured channel properties

	Sound Speed Profile	Water Depth (m)	Range (km)	Source Depth (m)	Receiver Depth (m)	Multipath Spread (-15 dB)	Spatial Coh. ($\rho_{0.8}$)	Temp. Coh. ($\tau_{0.8}$)
AUVFest07 Calm Sea	Nearly Constant	20	5	19	17.2-19.2	~ 5 ms	~ 0.2 m	~ 30 sec
AUVFest07 Rough Sea	Nearly Constant	20	2.3	19	17.2-19.2	~ 20 ms	~ 0.2 m	~ 0.1 sec
UNet06	Downward Refractive	60	3.1	21	29.2-30.91	~ 10 ms	~ 0.2 m	> 10 sec
TREX04	Downward Refractive	70	3.5	40	39.6-41.22	~ 5 ms	~ 0.2 m	~ 0.2 sec

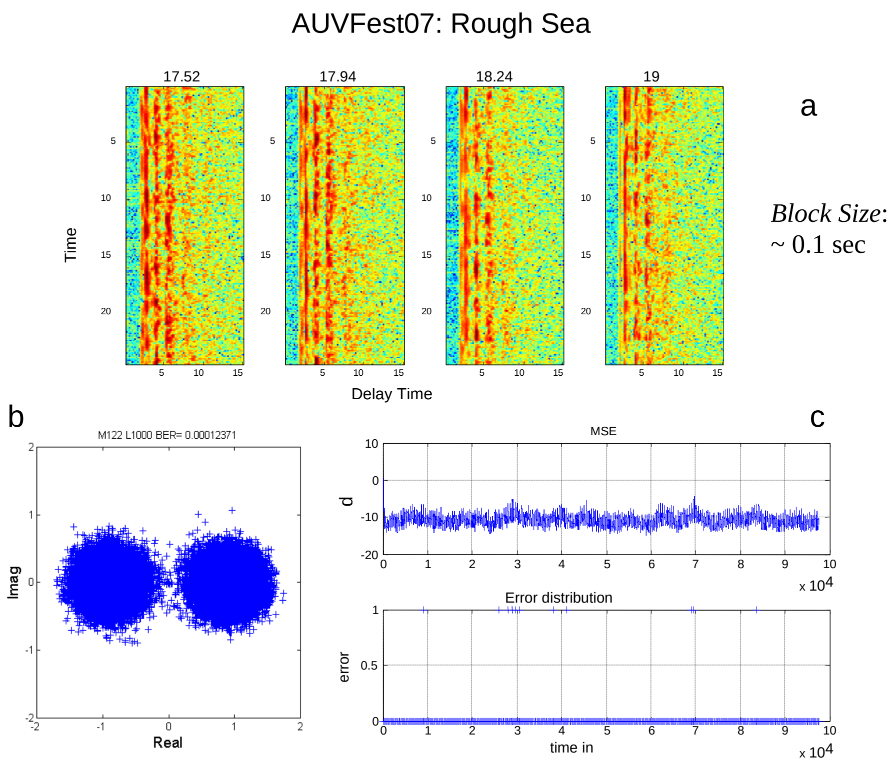

Figure 4. Variation of the channel impulse response with a 25 sec packet (a). The symbol constellation plot (b) and the MSE (in dB) and symbol error distribution (c); BER = 0.01%

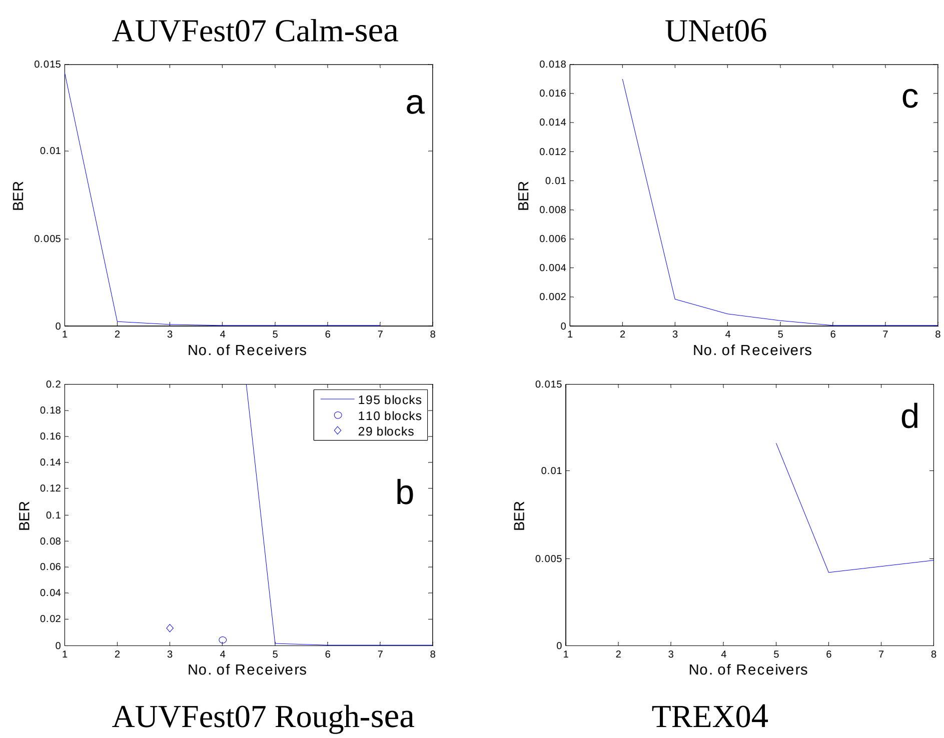

Figure 5. BER as a function of the number of receivers during the various experiments

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