A BLIND MULTICHANNEL COMBINER FOR LONG RANGE UNDERWATER COMMUNICATIONS

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ABSTRACT

This paper presents the development and performance of blind algorithms for a spatial diversity scheme to enable reliable data telemetry over a long range underwater acoustic channel. A number of Bussgang based stochastic gradient algorithms were tested for this multipath channel with additive white and coloured shipping noise. Both simulation and real experimental tests have shown that a significant improvement is obtained by utilising the spatial diversity of the long range channel and the ability of the combiner to perform joint equalisation and carrier phase tracking.

1. INTRODUCTION

Long range underwater communication systems are currently required for several applications such as environment control and oceanographic surveys. A typical scenario is presented by bottom mounted seismographic sensors transmitting data via acoustic sources situated in mid water to a central receiving station near shore. Performance of data telemetry systems used in long range underwater channels is limited by many difficulties, particularly so for horizontal links. Over long distances signal attenuation limits transmission to low carrier frequencies and hence low data rates. Therefore, bandwidth efficient schemes, such as PSK, are of prime importance. The channel also suffers from time varying multipath and phase fluctuations. Time varying multipath introduces inter-symbol interference (ISI) which can span many symbols, and phase fluctuations which can severely degrade coherent PSK modulation. The characteristics of such a channel are depicted in figure 1, which shows typical channel impulse responses as seen by two different elements with ~60 m spacing in the same near shore water column.

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The impulse responses clearly show that the long range underwater channel is nonminimum phase, and is characterised by a number of propagation paths emanating from a single transmitter. These paths can be considered as independent channels having different fading characteristics.

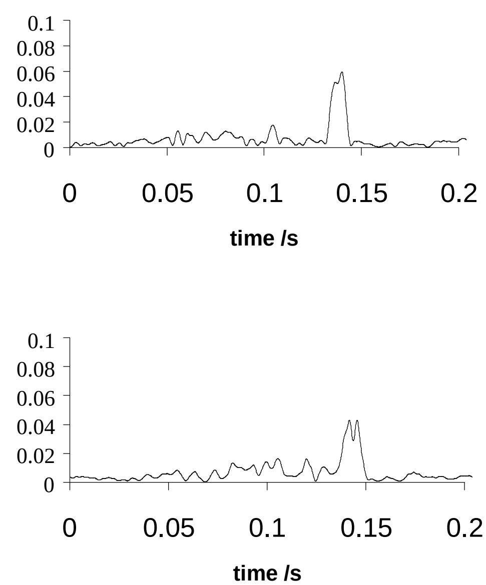

Figure 1 - Channel impulse responses at two different elements of the receiver array

Considering the aforementioned channel characteristics this paper presents a receiver scheme that performs joint blind adaptive equalisation and phase tracking of each independent channel as well as channel combining, thus further exploiting the spatial diversity introduced by the independent channels.

2. ADAPTIVE RECEIVER STRUCTURES

A number of adaptive receiver schemes have been considered to deal with the problems encountered in this channel. Single channel equalisation (linear and decision feedback) have been shown to be ineffective in producing a significant reduction in ISI [1]. It can be observed from figure 1 that the channel impulse response time spread spans ~100ms. This implies the need for a very long equaliser which will have inherently poor convergence and tap noise enhancement. A decision feedback equaliser is also unsuitable for this nonminimum phase channel with late dominant arrivals. Adaptive beamforming may at first be considered useful. However, whereas this is true for short range high data rate channels [2], in long range low data rate channels the angular response changes much more rapidly, thus presenting difficulties for beamformer tracking [1]. An alternative approach is one that exploits the spatial diversity of the independent channels by adaptive multichannel combining using a widely spaced sensor array [3,4]. This, in essence, is similar to adaptive beamforming using a narrowly spaced array. However, rather than adjusting the weights to produce a particular beam pattern for a single channel, the multichannel combiner effectively observes different channel exhibiting independent fading. The received diversity signals are weighted in proportion to their desired SNR, and then coherently combined to maximise the output SNR.

3. COMBINER ALGORITHM

The multichannel combiner structure is shown in figure 2. Its performance was tested using BPSK signals (212.5 symbol/s, 1.7 kHz carrier frequency) transmitted from an acoustic transducer 50 km offshore in the Mediterranean to the receiver array positioned near shore and spanning a water column depth range of 100m-301m. The received bandpass signals at each array element were pre-amplified and demodulated to provide complex baseband inputs (T/2 spacing) to the combiner's tapped delay lines. For the multichannel combiner shown in figure 2, the i^{th} element base band signal at time t=nT is given as:

$$u_i(t) = \sum_n d(n) g_i(t - nT) + v_i t\,, \qquad i=0, ..K$$

where $d(n)$ is the data symbol, $g_i(t\text{-}nT)$ is the overall impulse response of the i^{th} channel including transmit and receive filters and $v_i(t)$ is zero mean Gaussian noise. The output of the combiner is then given as:

$$\hat{d}(n) = \sum_{i=1}^{K} y_i(n)$$

where y_i is the output of the i^{th} tapped delay line:

$$y_i(n) = \mathbf{u}_i(n)\mathbf{w}_i(n)e^{-j\hat{\theta}_i(n)}$$

$\mathbf{w}_i(n)$ and $\mathbf{u}_i(n)$ are the vectors (for the i^{th} element) of tap weights and tap inputs, respectively, and $\theta_i(n)$ is the estimated carrier phase. The weights and carrier phase estimates for each combiner element are updated based on LMS adaptation:

$$\mathbf{w}_i(n+1) = \mathbf{w}_i(n) + \mu_w\, \mathbf{u}_i^*(n)\varepsilon(n)\mathrm{e}^{j\hat{\theta}_i(n)}$$

$$\hat{\theta}(n+1) = \hat{\theta}(n) + \mu_\theta\, \mathrm{Im}[y(n) f(n)]$$

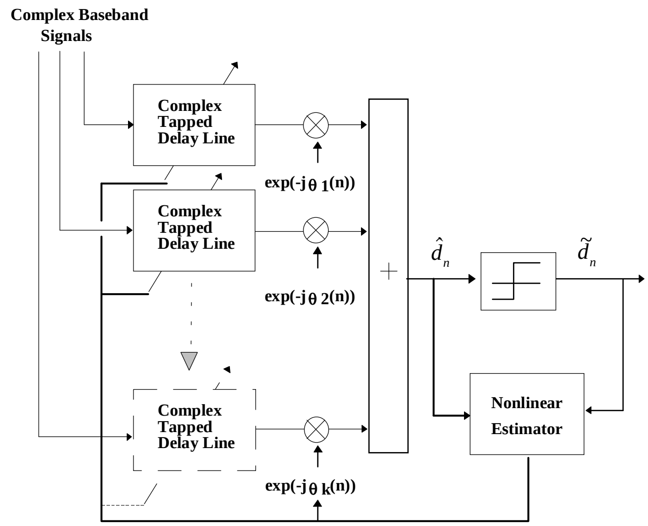

Figure 2 - Multichannel combiner structure

μ_w and μ_θ are adaptation constants, * denotes complex conjugation, and ε is a pseudo error signal given as:

$$\varepsilon(n) = g[\hat{d}(n)] - \hat{d}(n)$$

where $g(\bullet)$ is a memoryless nonlinear function that generates the desired response in the absence of a training sequence, and $f(n)$ is a decision directed function for carrier phase tracking. Convergence of this LMS-type algorithm is known to be achieved if the auto-correlation of $\hat{d}(n)$ equals the cross-correlation of $\hat{d}(n)$ and $g[\hat{d}(n)]$; such processes are know as Bussgang processes [4]. A number of these Bussgang algorithms have been reported for single channel equalisation of both one and two dimensional transmission systems. Here, we extend the use of these algorithms to multichannel combining with carrier phase tracking for BPSK signals. Although the functionality and performance of these algorithms is known to be different for *M*-ary PSK and QAM, they become, quite similar for BPSK signals. To test the performance of blind Bussgang techniques, two algorithms that were considered to be notably different were adopted with the following non-linear functions [6]:

$g[\hat{d}(n)] = \tilde{d}(n)$ Decision Directed (DD)

$g[\hat{d}(n)] = \hat{d}(n) + e(k_1 + k_2|e|)$ Benveniste-Goursat (BG)

where $e = \tilde{d}(n) - \hat{d}(n)$, k_1 and k_2 are constants.

These functions are specific to BPSK constellations, and further, the DD non-linearity function is, a direct simplification of the Sato algorithm [7]. Another well known Bussgang algorithm attributed to Godard [8] was also considered, however, its de-coupling of phase tracking and equalisation rendered it inapplicable to the structure proposed for the multichannel combiner.

4. RESULTS AND DISCUSSION

The algorithms detailed in the last section were tested for convergence speed, output SINR and BER for the 50 km underwater channel. This channel is known to exhibit multipath fading and random phase fluctuations as well as a small Doppler effect. Two tests were performed; the first with additive background white noise, and the second with more significant levels of directional (coloured) noise due to nearby shipping. Figure 3 shows phase constellation plots of the received signal for the first test before equalisation, single element equalisation, and 7 elements multichannel combining. The figure clearly shows that marked improvements in SINR are achieved using both Bussgang algorithms. It should be noted, however, that for this result, explicit carrier phase tracking was not necessary due to the insignificant levels of phase fluctuations that were adequately dealt with by the combiner forward equalisers. Convergence of the multichannel combiner is illustrated in figure 4 for the BG and DD algorithms (< 500 symbols). The BG algorithm is shown to converge to lower MSE levels than for the DD algorithm. This could be attributed to the robustness of the pseudo error signal of the BG algorithm and its ability to switch smoothly and automatically between blind start up and conventional equalisation during abrupt changes in the channel [6]. In the presence of shipping movement and noise near the receiver array, the received signals are smeared by coloured noise, and figure 5 (c & d) shows that for this condition, multichannel combining without explicit carrier phase tracking is still capable of an SINR improvement, albeit with residual tap phase rotation due to erroneous phase estimation by the equalisers. This, however, is improved by including a phase tracking loop that is simultaneously updated with the equalisers (figure 5-e & 5-f). For this channel condition, the MSE plots of figure 6 show that the BG algorithm has better convergence performance, and that phase tracking is better utilised by the DD algorithm as it lacks the robustness inherent in the BG algorithm.

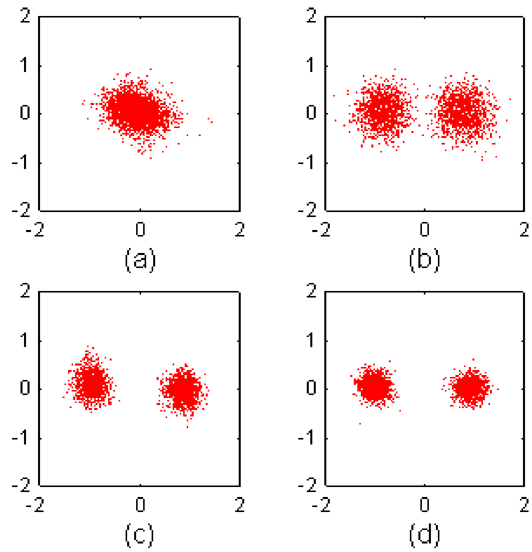

Figure 3 - Phase Constellations in the absence of shipping noise. a. before equalisation, b. single element equalisation, c. DD combiner, d. BG combiner.

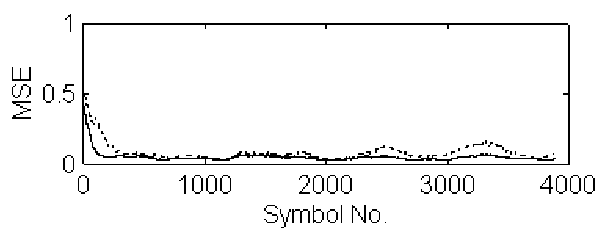

Figure 4 - MSE plots for the DD (dotted) and BG (solid) combiners.

The necessity for the multichannel combiner to jointly equalise and track carrier phase would be even more essential under severe Doppler phase shift due to movement or drift of the transmit/receive arrays. This effect is simulated by producing a ~1% carrier offset in the received signals thus resulting in the tap phase rotation shown in figure 6-e. The ability of the jointly adapted combiner is clearly illustrated in figure 6-f. The results (output SINR (dB)) obtained from both tests are shown in table 1 below for both blind Bussgang algorithms. BER, after convergence, were all of the order of < .5 x 10^{-3} for the 4000 symbol data records processed.

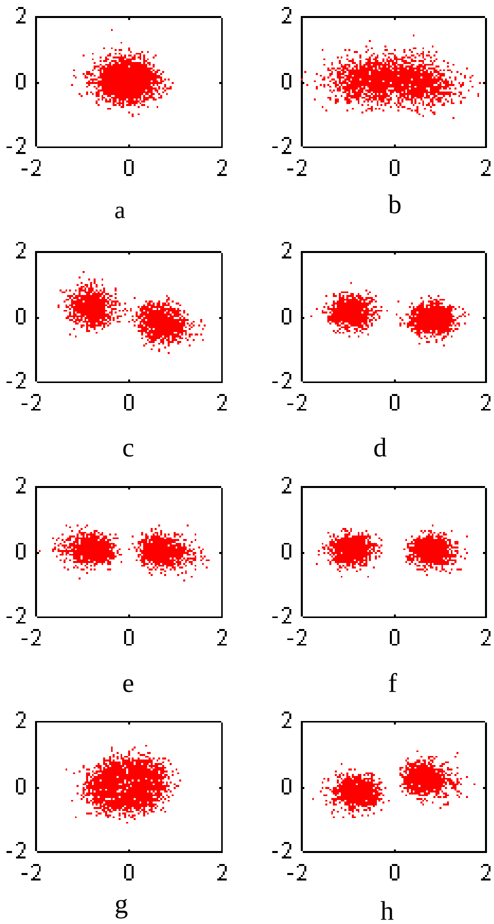

Figure 5 - Phase Constellations in the absence of shipping noise. a. before equalisation, b. single element equalisation, c & d. DD and BG combiner without phase tracking, e & f. DD and BG combiner with phase tracking, g & h. effect of ~1% carrier offset before and after phase tracking.

5. CONCLUSIONS

Blind multichannel combining has been shown to be an effective method for robust data telemetry in long range underwater channels. The adaptive algorithms presented in this paper were shown to achieve fast convergence and much improved SINR. During mild channel conditions both BG and DD algorithms achieved convergence (< 500 symbols) without the need for explicit carrier phase tracking. However, under more adverse channel conditions exhibited by nearby shipping and transducer movement, joint channel equalisation and carrier phase tracking was evidently required to track the fast phase fluctuations in the received signals.

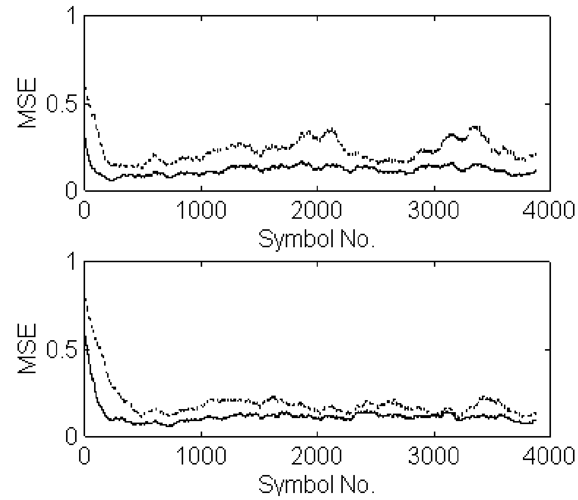

Figure 6 - MSE plots, upper: DD (dotted) and BG (solid) combiners with no phase tracking. lower: DD (dotted) and BG (solid) combiners with phase tracking.

Table-1	No Shipping		Ship noise	
	BG	DD	BG	DD
No Phase tracking	13.1	11.1	8.9	6.1
Phase tracking	13.2	12.2	9.4	7.6

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