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To cite this version:


HAL Id: jpa-00230466
https://hal.archives-ouvertes.fr/jpa-00230466
Submitted on 1 Jan 1990

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ADAPTIVE BEAMFORMING FOR ACOUSTIC COMMUNICATIONS

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Abstract - The basic factors which need to be considered in the design of a practical through water communications system utilising an adaptive beamformer at the receiver are examined. Simulation results demonstrate the feasibility of using such a scheme. It is clear that the multipath phenomenon which has proved so detrimental to a high data rate through water communications link may be effectively counteracted by employing such a system.

Introduction

The increasing number of oil and gas fields together with the cost and dangers of repairing subsea structures around these fields has led to the increasing use of remotely operated vehicles (ROVs) in order to carry out essential maintenance work. Other important applications include the transmission of sensor data from well heads, and the remote control and monitoring of blowout preventor stacks.

To date, these ROVs have used umbilical cables for communication, but with the great risk that the cable may become entangled, increasing interest has centered on the possibility of using a through water communication system for the control of the ROV.

The Through Water Communication Problem.

Through water communications is complicated by several factors. One of the most difficult problems to be overcome is that due to the multipath phenomenon. This causes inter-symbol interference in the receiver with the result that the transmitted symbol may be incorrectly detected.

Other factors which influence the design of a communications system are the attenuation of sound energy by the medium, and forward scattering caused by the various inhomogeneities in the medium, as shown in Fig 1.

As described in [1], it can be seen that the factors described above lead to a received signal which has a Rayleigh distributed amplitude fluctuation and a uniformly distributed phase. However the conclusion in [1] that conventional amplitude and phase modulation are unsuitable for through water communications are no longer valid for the situation in which the receiver is highly directional, as is the case for a system employing an adaptive beamformer at the receiver.

This leads to the possibility of using more efficient modulation methods which have not been considered viable in the past.

The requirement for a high data rate coupled with the limitations of the available transducer bandwidth lead to the requirement for a high carrier frequency. However, as the attenuation of signals in the sea increases with increasing frequency, a tradeoff must exist between a high data rate and the transmitted acoustic power.
A Scheme for Reliable Communications.

An overall block diagram of the proposed system is shown in Fig. 2. The transmitter has been implemented digitally and is therefore capable of producing a modulated data stream using any of the modulation formats which may be used in through water communications including OOK, FSK and PSK.

The receiver circuitry consists of some initial signal conditioning (amplification and filtering), a digital adaptive beamformer and a detector. The beamformer can be subdivided into two sections[2]; an adaptive algorithm and a reference signal extraction section.

By correlating the incoming signal vector with the reference signal, the mean square error at the output may be calculated, and it is this error which the adaptive algorithm attempts to reduce. It is clear that some ingenuity is required in order to generate a reference signal, as if the reference signal was completely known for all time there would be no necessity for a communications link.

The reference signal may be generated in many ways[3][4], the one chosen for our application being a modification of [4].

By interleaving a training sequence (completely known at the receiver) with the data, a reference signal may be extracted and used to train the array. The training sequence is sent periodically in order to allow the array to track a moving transmitter, as well as the changing direction of the multipath signals. If a simple correlation method is used to determine when the training sequence has been transmitted, the training sequence and correlation length need to be sufficiently long in order to guarantee that the reference signal may be extracted, as this procedure would need to be accomplished without any multipath protection being gained from the adaptive array. If a very long training sequence is required for reliable reference signal extraction, a delay lock tracking loop as described in [4] may be used in order to provide protection from the array whilst the array is being updated.

Design Parameters

Various parameters effect the performance of an adaptive beamformer for use in an underwater communications environment. The number of degrees of freedom offered by an N element array is N-1, and it is this that determines how many nulls and main-beams may be steered simultaneously. In an underwater environment, it is the number of multipaths which will determine the number of transducers which are required. Should the number of multipaths exceed N-2 (one degree of freedom is required to steer the main beam), the performance of the array will deteriorate significantly.

The spacial separation of the array elements is also of importance. The greater the physical separation of the elements, the greater the resolving capability of the array. However as shown in [5], should the element separation exceed \( \lambda \) (where \( \lambda \) is the wavelength of the highest signal frequency component), grating lobe effects may result.

Adaptive beamformers have found widespread use for HF links [6], where the fractional bandwidth \( B = \text{SBW}/f_c \) where \( \text{SBW} \) is the signal bandwidth and \( f_c \) the carrier frequency, is typically in the region of 1 - 2%. For such situations it is common to split the incoming signal from each element into an inphase and quadrature component using a quadrature hybrid, and weighting each of these signals with a real coefficient under control of the adaptive algorithm[6]. For an underwater communications scheme, since the carrier frequency is usually relatively low (<100KHz in order to keep the attenuation low), the fractional bandwidth \( B \) is often in the region of 40% and hence the performance of a system based upon the use of quadrature hybrids would be unsatisfactory [7].

Our work has shown that this may be overcome, as illustrated by the simulation results shown in Fig. 3. Fig. 3a shows how the array gain varies with frequency for signals arriving from the look direction. Here the signal bandwidth occupied a frequency range from 40KHz to 60KHz. It can be seen in Fig. 3a that the array bandwidth is approximately flat over this frequency range. Similarly Fig. 3b shows how the array sensitivity varies with frequency for signals arriving from the multipath direction. Whilst it is clear that the multipath attenuation at the carrier frequency of 50KHz is substantially greater than that
which is offered by the array at other frequencies, it can be seen that an attenuation of at least 13dB is afforded across the entire frequency band of interest.

The rate of adaptation affects the performance of the system in a number of ways. The rate of adaptation needs to be kept low in order to allow the system to converge. The misadjustment also depends upon the rate of convergence, and both of these lead to the requirement for a very slow convergence. For the method of reference signal generation which we have chosen, it is desirable to have the algorithm converge as rapidly as possible in order to maintain a high effective data rate, since in order to generate a reference signal it has been necessary to interleave a training sequence with the data stream. Obviously the quicker the convergence, the shorter the training sequence and therefore the higher the effective data rate.

Fig 4 shows a typical learning curve for the case of a single multipath of equal power to the direct path. Uncorrelated Gaussian noise was also present on each element, with a SNR = 0dB. It is clear that the algorithm has converged; the total time being allocated for the training sequence resulting in a reduction in the available bandwidth. Although a reduction in available bandwidth may appear to be too great a penalty to pay for the generation of a reference signal, it is far smaller than that which is commonly used [4], and it is believed that the overall increase in data rate which can be achieved by the use of the adaptive beamformer far outweighs this penalty.

**Results**

A typical beampattern plot and eye diagram are shown in Fig 5 and 6 respectively. These were obtained for a direct path power to multipath power of 0dB and E/no = 13dB. For this example the direct path signal arrived from an angle of 50 degrees whilst the multipath arrived from -40 degrees. It can be seen that the multipath signal has been attenuated by approximately 23dB with respect to the direct path signal. An eye diagram produced by demodulating the output of a single element is shown in Fig 6a, whilst a similar plot obtained by demodulating the output from the adaptive beamformer is shown in Fig 6b. It can be seen that the eye diagram is far wider in the second instance, corresponding to a BER of 1.5 E-2 by using the array output, compared with a BER of 0.239 without the protection of the array.

**Conclusions**

A brief review of the factors effecting the design of a through water communications system has been presented. The concept of using an adaptive beamformer to overcome the multipath phenomenon has been suggested, together with a description of the parameters which need to be considered when designing a communications link employing such a scheme. Various simulation results have been presented which demonstrate the potential for the scheme in an underwater environment. A real time implementation of a complete communications system is presently under construction, and it is hoped to gain valuable field results from this shortly.

**Acknowledgements**

We gratefully acknowledge the financial support of the SERC and the Marine Technology Directorate under the Automation of Subsea Tasks research programme.

**References**

Fig 1: A general Underwater Communications Link.

Fig 2: Overall system block diagram.

Fig 3: Frequency response of array (a) in look direction and (b) in multipath direction.

Fig 4: Typical learning curve.

Fig 5: Beampattern plot showing the array gain against angle.

Fig 6: (a) eye diagram obtained without the adaptive array and (b) eye diagram obtained with adaptive array.