THE DEVELOPMENT OF A RELIABLE HIGH SPEED DIGITAL COMMUNICATIONS LINK FOR UNDERWATER APPLICATIONS

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1. INTRODUCTION

Currently, many underwater tasks would benefit from the availability of reliable, tetherless Remotely Operated Vehicles (ROVs), which could operate at ranges up to 3 km or more. The use of tethered ROVs imposes several limitations as range, manouverability, and the ability to access enclosed spaces are all restricted by the presence of an umbilical cable. The purpose of the AIDA (Acoustics for Image DAta) project is to develop a framework of techniques which may be employed to guide the design of a large class of tetherless ROVs for a variety of applications. Specifically AIDA intends to investigate the feasibility of establishing a high data rate digital communications link between a ROV swimming near the sea bed and a surface vessel, to allow the transmission of high resolution images in real time. The major objective is to achieve very high data rates (150 Kbits/sec) over relatively short distances, e.g. < 1km, but the performance for ranges up to 3km will also be investigated, with expected data rates of > 20 Kbits/sec. AIDA is chiefly concerned with coastal and continental shelf regions, where the ocean depth is significantly less than the transmission channel length, forming a hostile environment for an acoustic communications system.

Typical systems in use today for underwater communications employ wide beamwidth transmit and receive antennas, with the surface vessel located directly above the ROV. Multipath effects are therefore negligible, link establishment being guaranteed at the cost of increased power consumption. AIDA intends to use highly directional electronically steerable transmit and receive antennas, employing modulation schemes with high spectral efficiency (e.g. QPSK, 8PSK). Adaptive beamforming and adaptive equalisation will also be employed to reduce the effects of multipath and inter-symbol interference. Typical geometry's for these two types of system are illustrated in figure 1.

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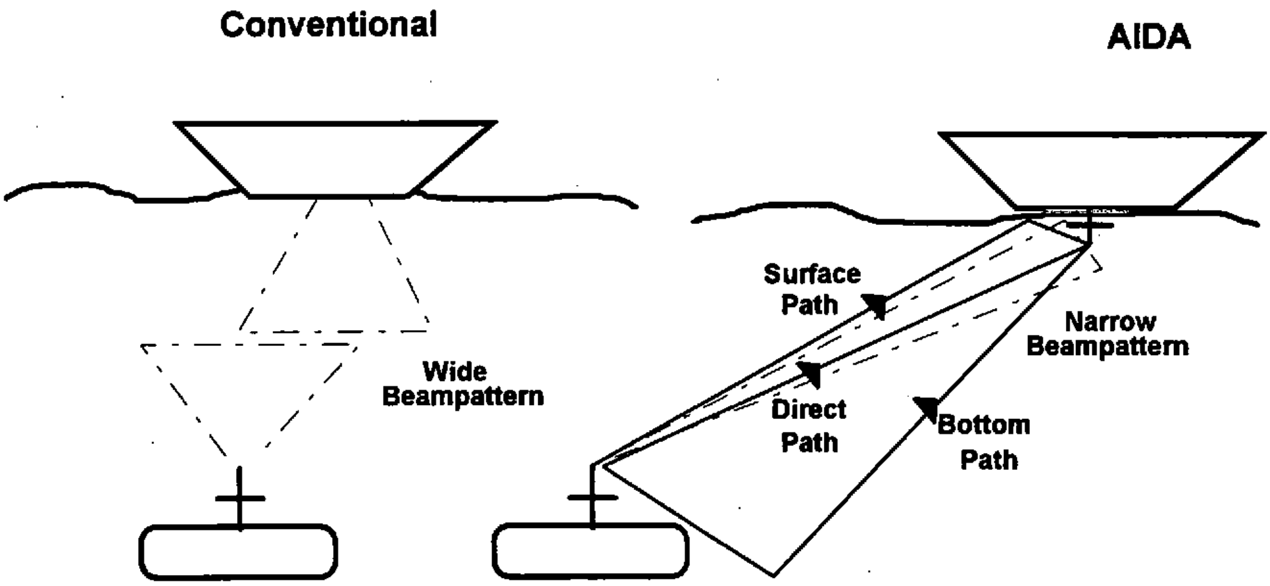

Figure 1: AIDA Compared to Conventional Systems

2. AIDA SPECIFICATIONS

The AIDA project has the following design objectives:

- To provide a reliable digital communications link for distances between 300m and 3 Km
- Transmission speeds should be between 20Kbits/sec and 150 Kbits/sec, to allow images acquired by a camera mounted on a ROV to be sent back to a surface vessel in real time, at a reasonably high resolution and frame rate
- Centre frequencies are 50 KHz (20Kbits/sec) and 200 KHz (150Kbits/sec), with corresponding bandwidths of 30KHz and 75KHz
- Investigate the use of different modulation schemes, with the aim of being able to automatically select the most suitable and efficient scheme for a set of prevailing conditions. The spectral efficiencies expected are ≥ 2 bits/Hz
- Employ adaptive beamforming to minimise the effects of multipath
- Employ adaptive equalisation to minimise the effects of inter-symbol interference

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2.1. Project Overview and Partitioning

The AIDA project is subdivided into five major components, each of which is being undertaken by a different partner. Thompson-Sintra (TSM) acts as the overall system designer, and evaluates the initial steady state and time varying system models. TSM is also responsible for final system integration. Technical University of Denmark (TUD) is implementing a suite of software to allow sophisticated channel modelling, generating output data for use by both the adaptive beamformer and the adaptive equaliser. University of Newcastle Upon Tyne (UNT) is responsible for evaluating an adaptive beamformer, implemented as a software simulator. UNT is also responsible for the design, implementation and practical use of a real time data acquisition system, to allow the acquisition of large quantities of real signal data during sea trials. CEPHAG is responsible for the design of an adaptive equaliser, also in the form of a software simulator, which will eventually be linked to the output of UNTs adaptive beamformer. Finally, RESON systems is responsible for designing and testing the ROV mounted transmit antenna. This antennae should be electronically steerable, be capable of handling wide band signals (60% of centre frequency), and have a beamwidth of approximately 10 degrees.

2.2. Novel Aspects of AIDA

Taken individually, none of the technical issues addressed by AIDA are novel, but combined into a systems optimisation problem, the AIDA specification should enable considerable advances to be made in several important areas of underwater acoustic communication system design, e.g. adaptive communications with an autonomous vehicle. The combination of an adaptive transmitter, capable of altering the data rate and/or modulation scheme to suit the dynamics of the transmission channel, coupled to highly directional transmit and receive antennas, and the real time use of both adaptive beamforming and adaptive equalisation, forms the basis of a flexible and powerful communications system.

By transmitting a pseudorandom sequence of suitable duration down a communications channel, analysing the effects of the channel on the data, and instructing the transmitter (over a command and control telemetry link) to modify either the rate of transmission, the modulation scheme used, or both, it may be possible to incorporate into a system a degree of flexibility which would ensure that communications were dynamically maintained at an optimum level, even if the channel characteristics were time varying.

2.3. Major Technical Issues Tackled in AIDA

AIDA provides a sophisticated channel modelling tool coupled with the ability to record large quantities of real data during sea trials to provide a realistic means for evaluating the performance of both individual system components and the overall communications package. It is intended to incorporate the effects of Doppler shift caused by the relative motion of the ROV and surface vessel, and also (if proved significant) the Doppler shift caused by surface wave motion, into any

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system analysis performed using either real data acquired by UNT or synthetic data generated by TUDs channel modelling tool. The problem of dynamically aligning the transmit and receive antennas, using a beamwidth of only 10 degrees, should be solved by developing a suitable adaptive beamformer. The data rates specified by AIDA, e.g. 150 Kbits/sec at ranges between 300m and 1 km, push beyond those set by any reliable underwater communication system developed to date, and should clearly demonstrate the bounds of what can be expected to be achieved using today's state of the art communications technology.

3. CHANNEL MODELLING - TECHNICAL UNIVERSITY OF DENMARK

TUD is undertaking the task of developing a suitable software simulator (written in C, the language chosen as standard for use in AIDA) to supply realistic synthetic data for use by both the adaptive beamformer (designed by UNT) and the adaptive equaliser (designed by CEPHAG). Several methods are under investigation, including finite element analysis, and analytical methods. Ray tracing has proved to be the most promising technique so far and is currently being used to develop a modelling tool. Ray tracing allows an arbitrary sound velocity profile to be used, and is reasonably efficient computationally, although long computation times are still required (using a 386PC) to generate useful amounts of data.

The channel model will eventually allow for relative motion between the transmitter and receiver, to take into account the movements of both the ROV and the surface vessel. The sea state is modelled by generating a pseudorandom sea surface from a knowledge of the windspeed 19.5 metres above the sea surface. The Pierson-Moskowitz model is used to generate a one dimensional dynamic rough surface [1]. A coherent signal representing the energy reflected from the sea surface is then calculated using the Kirchoff approximation [2]. This method assumes three things:

1 The grazing angles of acoustical energy incident on the sea surface must be greater than 20 degrees

2 The Pierson-Moscowitz model only holds if the sea depth is greater than 20 metres

3 An open channel is assumed, i.e. no side reflections are present

4. ANTENNA DESIGN - RESON SYSTEMS

The AIDA project requires efficient, electronically steerable transducers with wide bandwidths, e.g. approximately 60 % based on a centre frequency of 200 KHz. Initial work began on selecting suitable materials for this application, and testing single element models to operate in the required frequency range. This work then progressed to arrays without taking into account interaction, and then to arrays with interaction. Both analytical and finite element techniques have been employed to analyse the various types of array under investigation. Another important consideration for AIDA is sound velocity variations in materials such as ceramics, due to the wide bandwidths involved. It is thought that coarse mechanical steering will be used coupled with fine electronic steering to provide the necessary accuracy for dynamic alignment required in AIDA.

5. DATA ACQUISITION AND BEAMFORMING - UNT

5.1 Data Acquisition

The data acquisition system selected by UNT for use in the AIDA project had to fulfil the following broad requirements:

- Simultaneously record 8 channels of data with high accuracy (e.g. S/N > 80 dbs, 14-bits)
- Record continuously for several seconds (a minimum of 5 seconds), with intervals of several minutes between successive recording activities
- Have the capability to perform data analysis off line, and possibly preprocessing, e.g. down conversion, in real time.
- Provide an upgrade route to allow the bandwidth per channel to increase from 200KHz to 1 MHz, with a minimum five second continuous record capability

This is a very demanding specification to meet, and considerable time and effort was spent investigating various options, e.g. digital and analogue tape systems, bus based architecture's and proprietary hardware, before a system manufactured by Loughborough Sound Images (LSI) was finally selected due to its modern, flexible and expandable structure, high performance specification and cost effectiveness.

5.2 The C40 Data Acquisition System

LSI manufacture a number of C40 based boards, designed around the TIM-40 module standard, which can be used to implement flexible and scaleable processing and/or I/O intensive systems. The number of channels, I/O bandwidth, and processing power per channel can all be increased by adding more TIM-40 modules and extra motherboards. At present the system used by UNT, illustrated in figure 2, comprises one mother board populated by a single C40. This system is capable of handling the data from eight I/O channels simultaneously, each channel having a 200KHz throughput. As the A/Ds used are 16 bit, two samples from each A/D are combined to form a single 32 bit C40 data word. The aggregate data rate through the C40 is 3.2 megabytes/second. A 64 megabyte DRAM module has been purchased to allow continuous real

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time storage of data for up to 20 seconds. To accommodate the higher frequency tests, e.g. eight channels running at 1 MHz each, a second motherboard populated by another C40 will be added. The aggregate data rate through each C40 will then be 8 megabytes/second. A second 64 megabyte DRAM module will also be added, allowing data at the higher rate to be stored continuously for up to 8 seconds. Overall control of the VME based C40 data acquisition system is provided by a portable PC. The PC sets up the C40 in the correct mode to acquire data, transfers program code to C40 memory during initialisation, and reads back the data captured by the C40(s) to PC memory for analysis and storage on DAT tape. Signal processing and signal analysis will probably be achieved using a combination of the C40(s) and a signal processing package located on the PC, e.g. DADiSP.

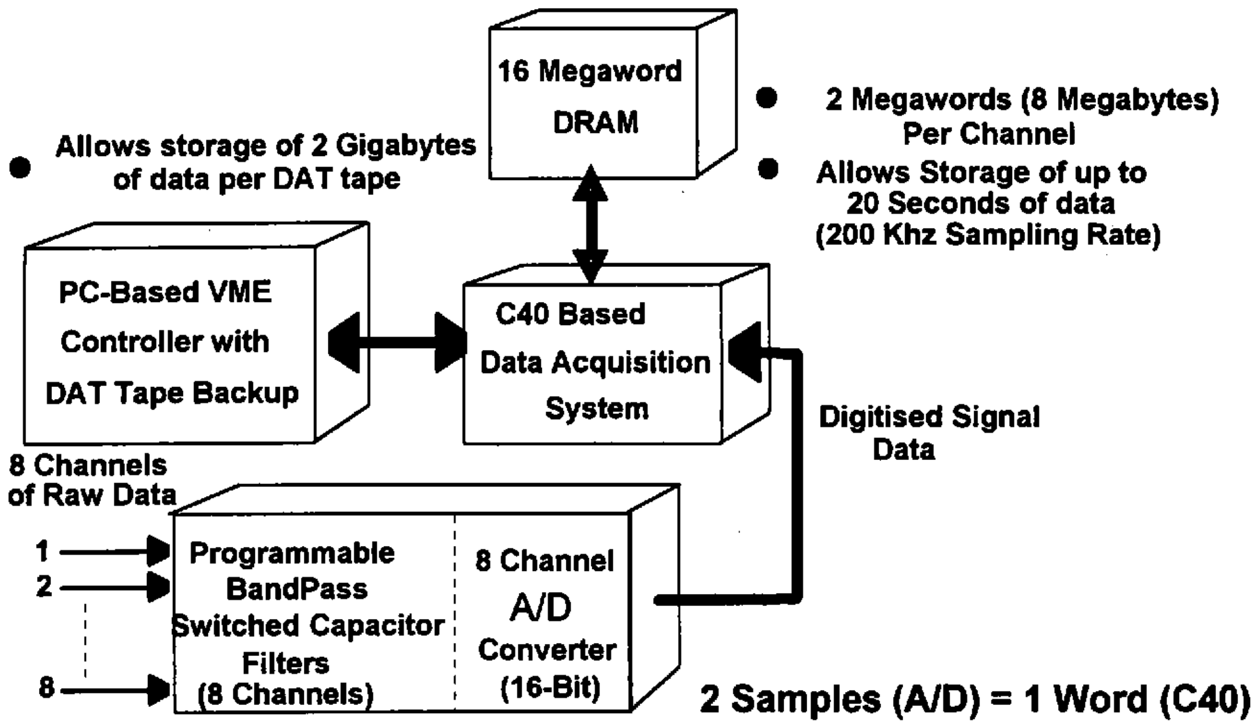

Figure 2: The C40 Based Data Acquisition System

5.3 The Transmitter Design

The transmitter design used for the AIDA tests is illustrated in figure 3. A microcontroller is employed to supervise the operation of a number of logic blocks which are used to reproduce a variety of modulated signals stored in EPROM's. The data read from an EPROM is converted into analogue form by an A/D converter, and forwarded via a programmable smoothing filter and a

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power amplifier to the transmit antenna. Overall control of the transmitter by a user is accomplished through a menu system located on a portable PC, to which the microcontroller is linked over an RS232 port. This system is quite flexible, as the data for transmission can be altered by either replacing the code in an existing EPROM or by adding more EPROM's. Any sequence(s) of data can be selected for transmission, the microcontroller simply re-programs the relevant logic blocks to allow the new task to be performed on command from the user, via the PC menu.

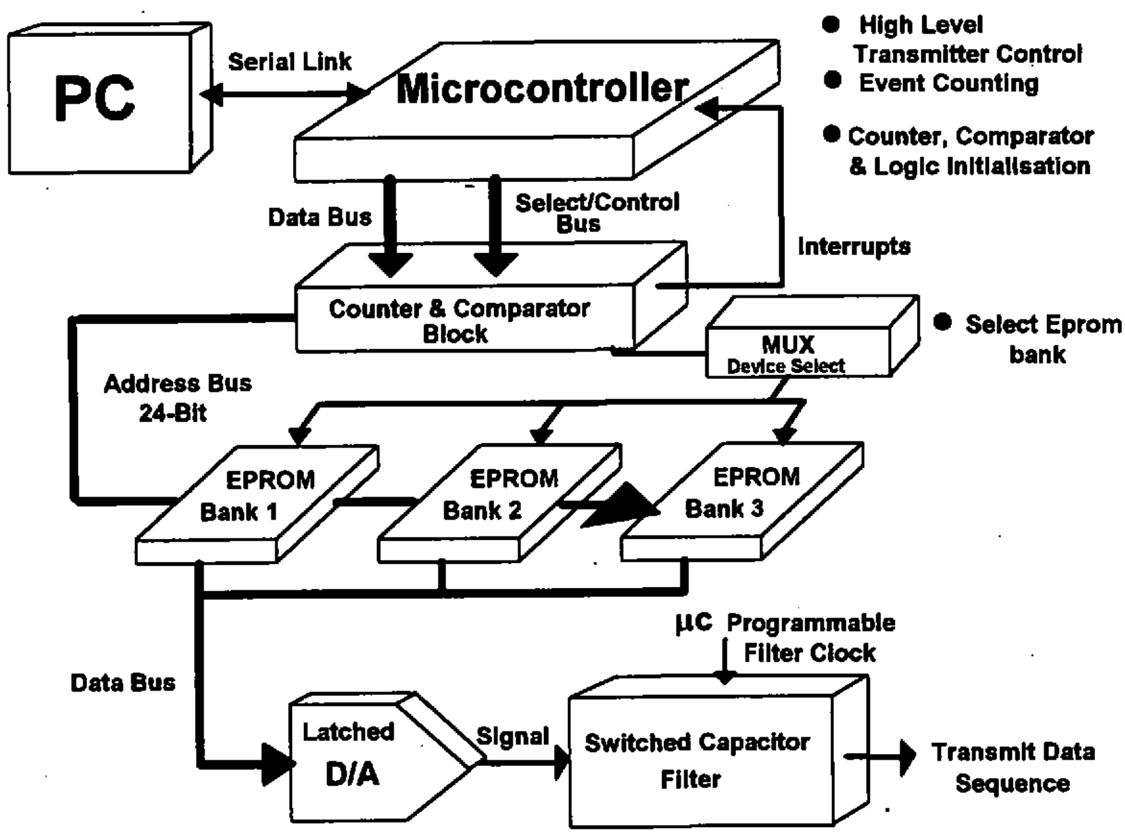

Figure 3: The Transmitter Design

5.4 Adaptive Beamforming

The basic objective of an adaptive beamformer is to identify a set of complex weights for modifying the outputs of an array of sensors so as to produce a far field pattern that optimises the reception of a target signal along a direction of interest in some statistical sense. Typically this means maximising the Signal to noise ratio with respect to a desired signal. A typical architecture for a beamformer is shown in figure 4. The structure comprises N sensors, which may have uniform or non-uniform spacing, and a linear combiner with N adaptive weights. The control law governing the adaptation process typically solves the Wiener-Hopf equation (Eq.1) where $\varnothing xx$

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represents the autocorrelation matrix of the input signal vector, *Wopt* is the ideal weight vector, and $\varnothing xy$ is the cross correlation vector between the input signal and the desired signal

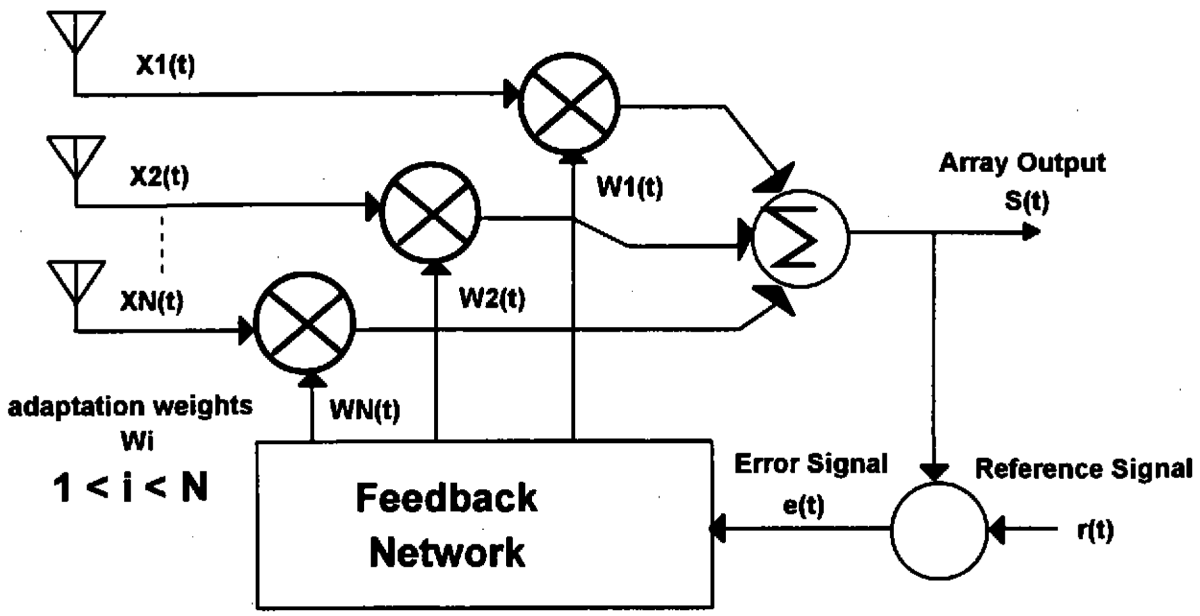

Figure 4: Typical Architecture of an Adaptive Beamformer

$$\varnothing xx\, W_{opt} = \varnothing xy \qquad \text{(Eq. 1)}$$

There are a variety of methods available which can be used to obtain a dynamic estimate for the weight vector *Wopt*, the most popular ones being the Least Mean Squared (LMS) stochastic gradient method, and the Recursive Least Squares (RLS) methods [3]. These two approaches have widely varying characteristics, the LMS being simpler to implement with minimal computational overhead ($O(N)$), while the RLS is more computationally intensive ($O(N^2)$) but has superior operational characteristics. A number of fast algorithms are available which may be used to reduce the computational overheads involved in the RLS algorithm, e.g. the fast Kalman algorithm and Lattice structures. The advantage of using the RLS method is that convergence times are generally faster than those obtained with LMS, and do not depend upon the statistics of the data (LMS convergence times depend upon the spread of the eigenvalues in the input signal matrix).

UNT aims to develop a software simulator which can be used to investigate the performance characteristics of a small range of adaptive beamforming algorithms. Algorithms which are candidates for investigation for AIDA include LMS, LS, RLS and Kalman. The LMS algorithm will be implemented first, and will be used as a benchmark for other algorithms.

The use of the LMS approach offers several advantages when compared to alternative algorithms, e.g. it is simple to implement, convergence is guaranteed as the mean square error surface is parabolic, and it is computationally efficient thus allowing real time operation. Disadvantages of the LMS approach are that convergence can be slow and is data dependant, and that a reference signal is required. The reference signal can be difficult to generate, as it must be correlated with the desired signal, but uncorrelated with both interference signals and noise [4]. The LMS algorithm can track and hold a signal without having any a-priori knowledge about its arrival direction.

Other algorithms can be employed for beamforming, providing some knowledge about the arrival direction is made available, e.g. Applebaum, Shor [5]. Such algorithms allow fast convergence and do not require a reference signal. UNT proposes to investigate the use of such techniques when coupled to a suitable direction finding algorithm. Thus, it may be possible to use a direction finding program first to estimate the angle of arrival of a desired signal, then pass this information to the beamforming algorithm which will then locate and maintain lock on the desired signal. Alternatively, it may be necessary to repeat the direction finding process on a regular basis, to ensure that lock is accurately maintained on a desired signal.

6. ADAPTIVE EQUALISATION - CEPHAG

CEPHAG are currently investigating adaptive equalisation techniques for AIDA. Several different equaliser architecture's are under investigation, utilising both transversal and recursive filtering techniques. It has been shown how a recursive filter with a few taps (e.g. 8) can provide a speed of convergence and accuracy, with a far lower computational load, comparable to that obtained using a transversal filter with a large number of taps (e.g. > 60). The system proposed by CEPHAG employs a Costas loop for phase locking the signal, and an adaptive bit synchroniser using eight times oversampling. Figure 4 illustrates the structure of the adaptive equaliser.

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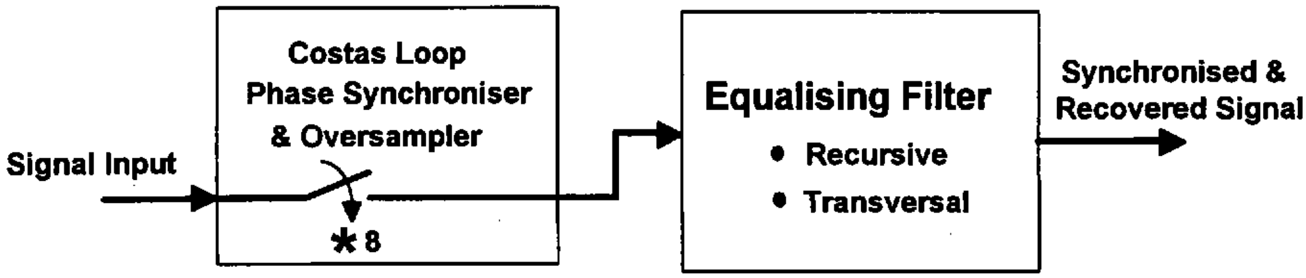

Figure 4: Adaptive Equaliser Architecture

The bit synchroniser is located first in the signal path, e.g. directly following the adaptive beamformer, as it has been found to be less sensitive to noise than the equaliser. The stability and performance of the recursive structure is still in question, and is being analysed further. A decision directed form of adaptive equaliser is also being considered, as is the feasibility of implementing a two path equaliser, one path employing a recursive filter structure while the other path employs a transversal filter. Intelligence may be needed to decide which path should be used at any instant, based upon a measure of the accuracy of the results achieved by each filter. This would make the system more flexible and responsive, as a faster recursive adaptive filter may be employed when stability is guaranteed (e.g. the signal to noise ratio was high enough), a switch being made to a slower but more stable transversal filter only when the recursive filter output became unreliable.

References

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