Development of the "Seatrac" miniature acoustic modem and USBL positioning units for subsea robotics and diver applications

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***Abstract*— As part of the EU FP7 project CADDY, an efficient and reliable acoustic communication network is required to connect a diver, autonomous underwater vehicle (AUV) and surface vehicle (ASV) working cooperatively. This paper describes the development of the modulation, receiver algorithms and miniature hardware platform for multi user communication and simultaneous positioning. Experiments using vehicles in the Adriatic, North Sea, enclosed docks and lakes have demonstrated reliable communication and positioning using a 100bps chirp based signaling scheme. Equally promising results are presented for experiments with a 1.4kbps direct sequence spread spectrum (DSSS) variant, currently being implemented on the same platform, which demonstrates remarkable tolerance of extreme multipath channels and noise using a relatively low complexity receiver algorithm.**

Keywords—underwater acoustics; acoustic modem; spread spectrum; positioning; USBL

I. Introduction

The FP7 CADDY project aims to produce a cooperative network consisting of a diver, small AUV and small ASV to improve the safety and effectiveness of diving operations as shown in Fig. 1. Based on the CADDY partners' experience with commercially available acoustic modem/tracking technology, it was felt that existing devices were too physically bulky and/or limited in performance to achieve the project goals. For this reason Newcastle University, together with commercial partner Blueprint Subsea, were tasked with developing a system to meet the needs of this ambitious project.

The initial CADDY demonstration scenarios require relatively low data throughput, for command, status and position messages, but with high robustness and frequent (< 2s) position estimates. This favoured a highly robust spread spectrum signalling scheme, based on orthogonal chirp waveforms, which allows direction of arrival to be simultaneously estimated from a miniature ultras short baseline (USBL) array. As the project develops, more data intensive operations are targeted so this has led to the development of a higher rate DSSS signalling scheme, with only minor degradation in reliability, which will also support the calculation of simultaneous USBL position fixes.

The key requirements for the system to be developed for the CADDY project are summarised below:

- The diver and vehicle mounted transceiver units must be of similar size and weight to previously used miniature technology e.g. Tritech Micron.
- Data rates of at least 100 bps, rising to at least 1kbps in future variants, to be maintained in extreme multipath environments and with Doppler effects from vehicle motion.
- Efficient protocols to maintain high payload throughput on short messages used in closed loop control.
- The miniature transceiver units must be capable of locating other units with < 2 second update period.
- All acoustic signals to be above the audible frequency range (> 20 kHz) for diver compatibility.

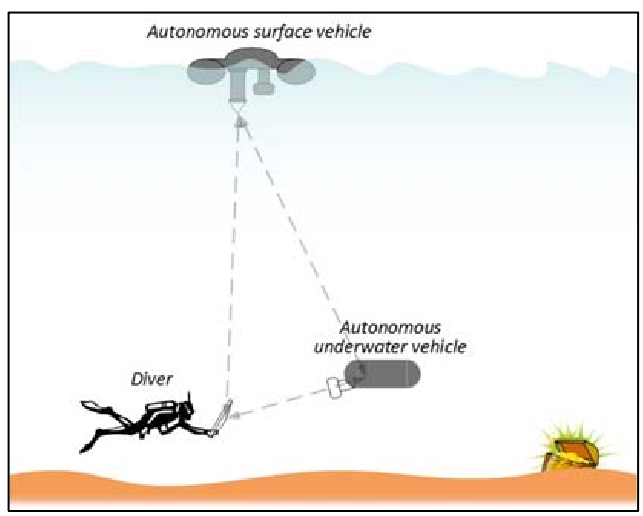

Fig. 1. The CADDY system concept.

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II. System Development

A. Hardware platform

The “Seatrac” hardware platform has been developed by Blueprint Subsea with the acoustic front end specified by Newcastle University. The combined modem/USBL units, shown in Fig 2, are designed as a very compact assembly measuring 160mm high by 55mm diameter. The acoustic front end is designed to operate in the band 24–32kHz, with a single PZT transmitting element and 4 smaller PZT elements above forming a 3 dimensional USBL array. Acoustic modem and USBL signal processing is implemented using a 150MHz ARM Cortex M4 processor as a low power “system on chip” solution. 4 on board simultaneous 16-bit ADCs enable capture of received signals from the USBL array. A high speed pulse width modulation (PWM) output is used to drive a highly efficient class D amplifier which synthesises the transmitted signals. This enables an extremely compact transmitter circuit capable of delivering source levels up to 176dB re 1µPa @ 1m with minimal thermal design considerations. The units also include a pressure (depth) sensor, temperature sensor and 3 axis gyro, accelerometer and compass (AHRS) to enable platform motion, sound velocity and depth to be used on board to compute enhanced position fixes. The stainless steel housing is rated for >4km depth although the electronics + transducer may be repackaged for OEM applications on vehicles.

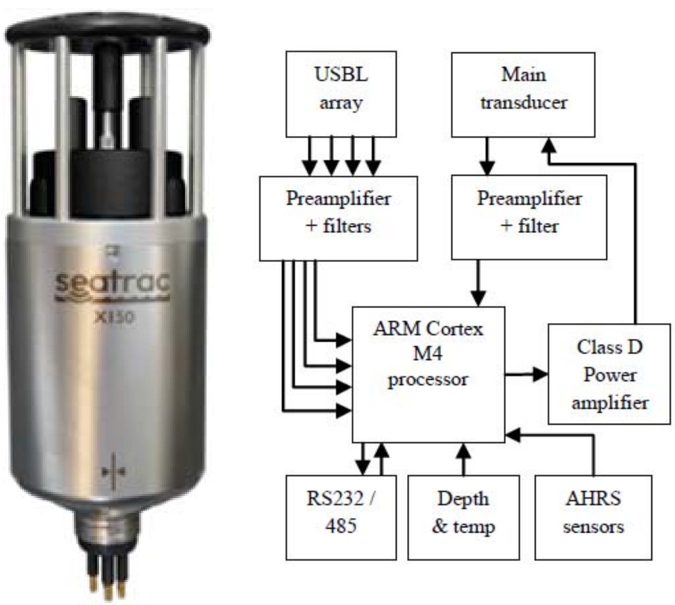

Fig. 2. Seatrac hardware platform

B. Low data rate spread spectrum transmission

The low data rate spread spectrum mode of transmission uses a well proven technique where two orthogonal linear frequency modulated signals (LFM), more commonly referred to as chirps, are used to convey binary data. A similar scheme has proven extremely robust in products previously developed by Newcastle. Furthermore, computationally efficient routines have previously been developed for fixed point receiver processing on relatively low cost, low power processors. Fig. 3 and 4 describe the signalling scheme and the receiver structure respectively.

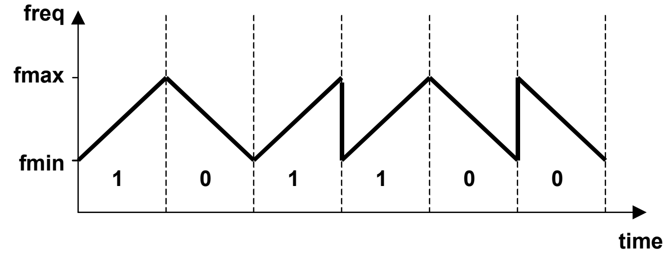

Fig. 3. LFM chirp modulation scheme

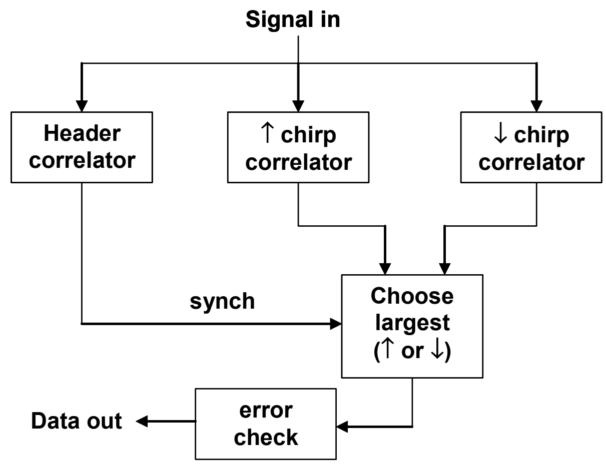

Fig. 4. Receiver for LFM chirp modulation

Data packets consist of a longer duration header chirp (50ms), followed by a series of data bits modulated as up or down chirps of 10ms duration (giving a data rate of 100bps). The receiver first correlates for the header chirp, to establish frame synchronisation, and then compares the outputs of two correlators matched to the up and down chirp waveforms. These correlator outputs are time gated relative to the frame synchronisation to only compare a small time window for each bit, so that inter-symbol interference due to multipath can be eliminated up to the length of the chirp. The chirps are swept over the whole available bandwidth (8 kHz) to give processing gain of 26dB for the header and 19dB for data bits. Due to the inherent Doppler tolerance of chirp waveforms, this scheme is also very resilient to platform motions, although block estimated Doppler correction can also be applied as in [1].

C. USBL positioning

USBL position fixes are estimated by calculating the phase shifts between signals arriving at elements of the miniature tetrahedral hydrophone array on the device (shown in Fig. 5). The spacing of the elements is 20mm, so as to be less than half wavelength spacing at all frequencies in the 24-32 kHz band and avoid any spatial ambiguities. The USBL algorithm utilises the same LFM waveforms used in communication packets, enabling simultaneous positioning and data exchange to be achieved. Each of the 6 inter-element phase shifts are calculated by comparing the complex values of the 4 LFM cross correlation coefficients so as to achieve a broadband, multipath resistant measurement. As shown in the results section, it is important that the optimum coefficient is chosen from the correlator output. In multipath channels it is essential that the USBL calculation is performed consistently on the first (most direct) signal arrival to avoid "ghost" positions due to reflected paths.

Fig. 5. USBL array construction

The inter-element phase shifts are fed into a simple optimisation algorithm to obtain the "best fit" estimate of the azimuth and elevation angles of the source relative to the array. The distance to the source is estimated by measuring the two way propagation delay, using the header chirp correlation output to provide precise timing. The resolution of range measurement is governed by the signal bandwidth and equates to approximately 10cm in range (absolute accuracy depends on accurate velocity of sound data). To obtain best results from the USBL and ranging, the on board temperature and depth sensors are used to estimate the sound velocity which is used in all calculations. Finally the computed relative position is corrected for the current attitude of the USBL head using the on board AHRS sensors.

D. *Medium data rate spread spectrum transmission*

In order to satisfy the requirements for more data intensive operations later in the project, a robust medium data rate (>1kbps) is required. The emphasis of this design is to achieve high reliability using only a single receiver hydrophone, whilst keeping the computational complexity of the receiver within the capability of the miniature, low cost hardware platform. Here we describe the modulation and receiver structure for a medium bit rate acoustic communication link, based on the principles of direct sequence spread spectrum (DSSS).

DSSS has proven to be an effective technique for combating inter-symbol interference (ISI) in the underwater channel but it has been shown that, due to the time variability of the channel and severe Doppler effects, a simple de-spreading operation in the receiver is unlikely to maintain the theoretical processing gain [3]. Hence adaptive filtering and phase/timing correction must ideally be applied to the received chips before de-spreading.

Conventional DSSS systems spread each symbol with a pseudorandom chip sequence, ideally a binary M-sequence to exploit ideal periodic cross-correlation properties. The symbol length in chips (spreading ratio), is then chosen to match the available sequence lengths (7, 15, 31, 63, 127, 255 etc) and to be longer in duration than the maximum expected channel time spread. The signal bandwidth of 8kHz available with this design allows a chip rate of 8kHz. However to achieve our target bit rates of at least 1kbps, the possible spreading sequence length would be at most 15 which corresponds to only 1.875ms duration. Since we wish to be tolerant of much longer time spread in this application, such a scheme would not be able to combat all ISI.

DSSS receivers can also be combined with complex decision feedback equaliser structures to combat longer delay ISI [4] but it is difficult to maintain performance/stability with a very large number of equalizer taps. Furthermore the computational complexity of such a structure would stretch capability of the proposed hardware platform. Hence we have investigated a variation of DSSS using a single very long M-sequence where each symbol is spread by a much shorter *L*-chip portion of this code. Whilst it is not possible to maintain ideal cross-correlation properties between different short segments of a longer code, it is found that this can effectively combat ISI in channels of extremely long time spread if combined with appropriate error correction coding.

LFM chirp (frame synch)	QPSK training sequence	(N,K) RS encoded QPSK symbols, each spread by an L-chip portion of 8191 chip binary code
50ms	31.9 ms	1.02s (for L=8, f_{chip} = 8kHz, N=255)

Fig. 6. Transmitted DSSS acoustic packet for 1.4kbps net throughput

The structure of a transmitted data packet is shown in Fig. 6. Each packet starts with a 50ms long LFM chirp waveform for frame synchronisation. This is followed by a 255 chip QPSK modulated sequence, derived from a maximal length binary code (M-sequence), which is used to train the adaptive filter and Doppler correction structure in the receiver. Finally Reed Solomon (RS) encoded data is modulated as a series of QPSK symbols, each spread by an *L*-chip segment of a longer 8191 point binary M-sequence. This spreading code cannot on its own guarantee to attenuate ISI on all symbols as short segments of the code will not be unique throughout the code. However it is found to consistently reduce the mean ISI to a level where error correction coding can eliminate remaining errors, regardless of the channel delay spread. By varying the values of *L* and the RS code rate (*K*), spread spectrum processing gain and error correction can be easily tuned to balance data throughput against channel conditions. The transmitter and receiver structures for this scheme are described in Fig. 7 and 8 respectively.

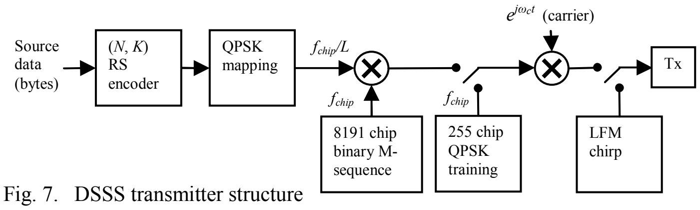

Fig. 7. DSSS transmitter structure

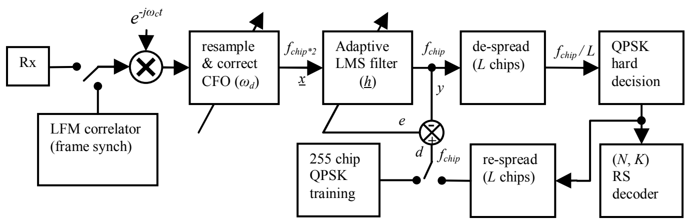

Fig. 8. DSSS receiver structure

The receiver first synchronises to the start of a transmitted packet by correlation for LFM frame synch waveform. The signal is then down-converted to a complex baseband signal and resampled by a factor R, using linear interpolation, to remove Doppler effects. This Doppler correction step also includes the removal of carrier frequency offset (CFO) estimated as ω_d. The estimation of both the resampling factor and carrier frequency offset is performed using techniques detailed in as in previous work by Newcastle University [5]. The re-sampler outputs two samples per chip which are fed into a linear adaptive filter.

The output of the adaptive filter is calculated at one sample per chip according to (1). The purpose of this filter is twofold: primarily to maintain precise phase and chip synchronisation but also to provide linear equalisation, combining the energy from multipath arrivals to increase the achievable signal to interference and noise ratio (SINR). Whilst complex non-linear equaliser structures can be effective on quite long delay spreads up to perhaps 100 symbols, the intention here is that the DSSS processing gain will be able to attenuate multipath of very long delay spread. Hence the adaptive filter is restricted to <40 taps to reduce computational load and maintain stability at low SNR. Nevertheless this does provide a useful gain through equalisation of short delay multipath arrivals. After the adaptive filter, the synchronised and equalised chip sequence is de-spread to recover the estimated QPSK symbols, a hard decision is made and the data finally decoded.

The adaptive filter coefficients are updated at the chip rate to maximise tracking ability. The error signal is calculated as in (2), where d[i] is the transmitted chip value which is either: taken from the a priori known training sequence; or estimated by re-spreading the QPSK hard decision output with the a priori known spreading sequence (decision directed mode). The adaptive filter coefficients are then updated as in (3), using the computationally simple least mean squares (LMS) algorithm, where μ is the adaptive step size.

$$y[i] = \underline{h}^T[i]\underline{x}[i] \tag{1}$$

$$e[i] = d[i] - y[i] \tag{2}$$

$$\underline{h}[i+1] = \underline{h}[i] + \mu e[i]\underline{x}^*[i] \tag{3}$$

The resampling factor, R, for Doppler correction must also be adapted. The phase error on the output symbols is calculated, as in (4), and this becomes our cost function for minimisation. A proportional control loop is then used to update the resampling factor as in (5), where k_p is the proportional tracking constant. Finally, the CFO (ω_d) is proportional to the estimated resampling factor and can be calculated as in (6).

$$\theta_e[i] = \arg\left(y[i].d^*[i]\right) \tag{4}$$

$$R[i+1] = R[i] + k_p\theta_e[i] \tag{5}$$

$$\omega_d = \omega_c\left(R[i]-1\right) \tag{6}$$

III. Experimental Results

A. Testing of 100 bps spread spectrum transmission and simultaneous USBL positioning

The 100bps spread spectrum scheme and the USBL positioning algorithm were implemented on the Seatrac ARM processor platform and a small number of prototype devices were constructed for testing in realistic environments. Tests consisted of the exchange of short messages of up to 16 bytes between a pair of devices, with a USBL fix calculated from each exchange. Open water experiments, in Windermere UK, confirmed that the maximum range between a pair of devices for both communication and USBL fixes was at least 1.5km. Testing was also carried out in the same environment with devices deployed on Videoray and Seabotix ROVs to verify robustness to platform motions up to 2 m/s. As expected, packet delivery rates were between 95-100% at all ranges up to the maximum.

However the operating scenarios for the CADDY project generally involve much shorter range and more complex environments than open water with the potential for more challenging multipath channel conditions due to 2D boundaries. Here we present the results of testing in enclosed dock environments, known to present channel delay spread of up to 100ms and which have proven very challenging for other acoustic modem devices tested by the CADDY consortium. Fig. 9-10 shows an example of results from testing of a prototype USBL unit in a 10m deep, concrete walled marina. A series of pontoons allowed a Seatrac unit to be accurately placed in a series of georeferenced positions with high repeatability and almost zero motion. A total of 800 interrogations, from another USBL unit at the origin (0,0), were attempted across the various positions with only one communication failure (dropped packet) observed. This is despite the extreme delay spread and propagation further complicated by the presence of many boats around the pontoon. Fig. 9 shows the estimated positions in X-Y plane. Fig. 10 shows (a) the X-Z plane positions and (b) the standard deviation of position vs range. A fit error is also calculated to indicate the quality of the estimated position by comparing with the idealised set of phase angles for each position. As expected the variance on each position is dominated by variation of azimuth and elevation angle rather than range. From Fig. 10(b) we estimate that the standard deviation of position is approximately 1.5% of range corresponding to approximately 0.8 degrees in angle. This is a pleasing result for such a small USBL array with dimensions of only 20mm. Some distortion of the geometry is visible, showing up to 5 degrees azimuth error on some positions, and this is found to be the result of manufacturing tolerances on the dimensions of the prototype array and phase matching on the receiver amplifier/filter circuits. Hence, tolerances on the mechanical construction of the array and passive components have been reduced for future production of the device.

One important aspect of the USBL signal processing proves to be the selection of the optimum correlator coefficient for the phase difference calculations. It is crucial to select the earliest signal arrival (most direct path) to avoid false fixes and this can be non-trivial when several paths are closely spaced and of similar magnitude. Hence an adaptive thresholding and peak-detection algorithm is applied to ensure that the first signal arrival is consistently selected as shown in Fig. 11.

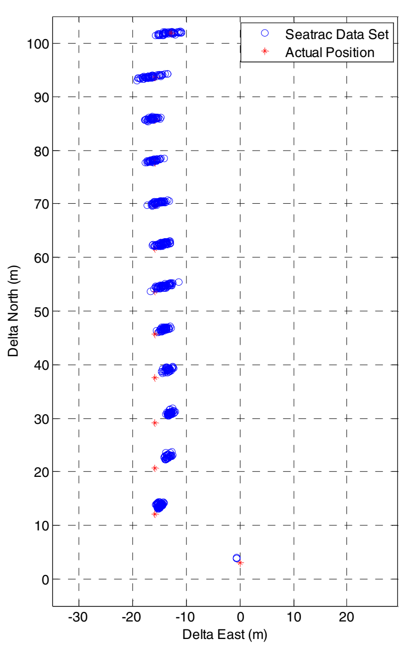

Fig. 9. USBL position estimates for dock trial (X-Y plane)

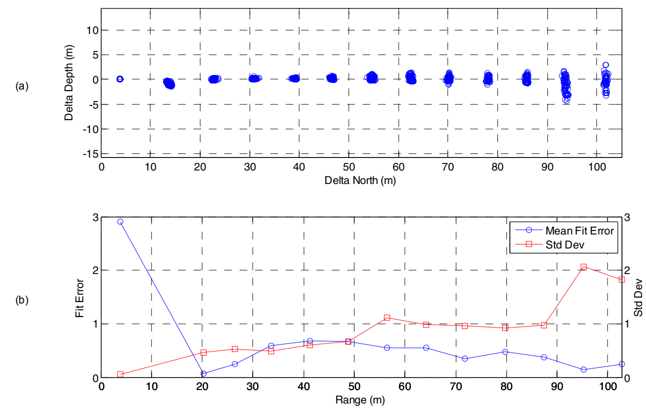

Fig. 10. (a) USBL position estimates for dock trial (X-Z plane), (b) standard deviation of position and mean fit error vs range

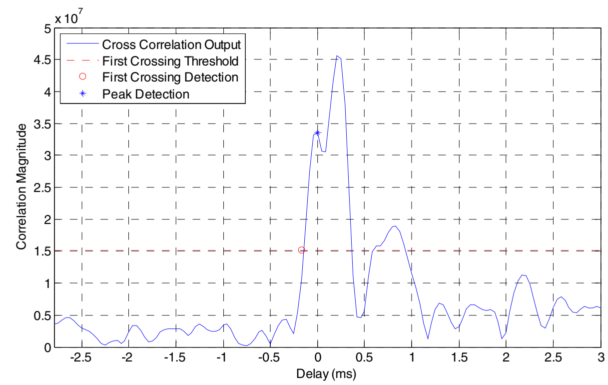

Fig. 11. Synchronisation to select optimum coefficient for USBL fix

Another example of testing in a very demanding environment was in a 50m outdoor poor in Croatia, 2-3m deep with concrete walls and rocky bed. In this environment the delay spread on acoustic signals was observed to be anything up to 1s with very complex multipath geometry in some areas e.g. corners. An experiment was carried out with a Seatrac USBL in a fixed position and another Seatrac unit moved around the perimeter of the pool at approximately half water depth. Fig. 12 shows the estimated positions overlaid on aerial imagery of the site. It is seen that effective communication and USBL positioning was achieved all around the perimeter of the pool with the whole path estimated to within approximately 1m standard deviation.

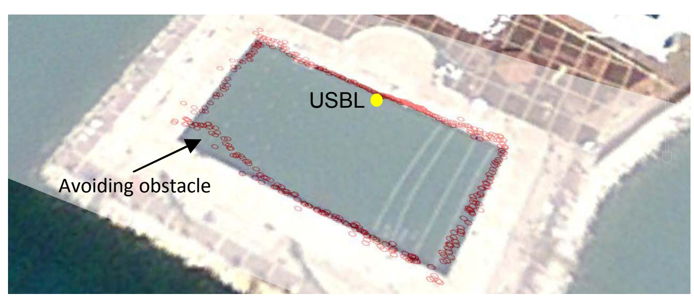

Fig. 12. USBL position overlay for 50m concrete pool

B. Medium data rate (1.4 kbps) spread spectrum transmission

Experimental transmissions of the proposed DSSS scheme have been carried out in a number of different shallow water channels with signals recorded and processed offline to establish the optimum receiver parameters. All results presented here used the system parameters listed in table I.

TABLE I. DSSS SYSTEM PARAMETERS

Parameter	***Symbol***	***Value***
Chip rate	f_{chip}	8000
Spreading ratio (chips/symbol)	L	8
RS code rate	(N,K)	(255,191)
Training sequence length	-	255 chips
Net data throughput	-	1.39 kbits/s
Transmit source level		174 dB re 1µPa
LFM chirp	-	B=8 kHz, T = 50ms
Adaptive filter length	-	36 taps
Adaptive step size	μ	0.02 training, 0.005 for data
Doppler tracking constant	k_p	2×10^{-5} training, 5×10^{-6} for data

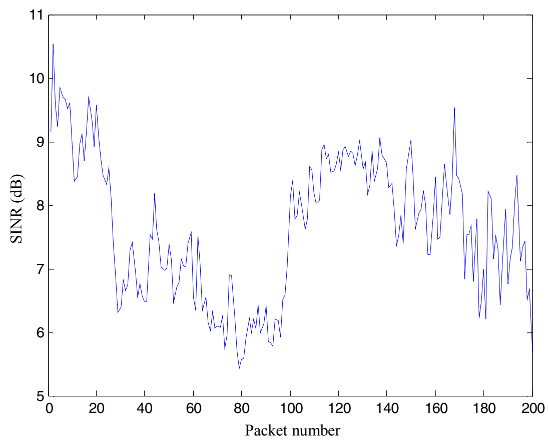

Fig. 13. Output signal to interference + noise ratio over 200 packets

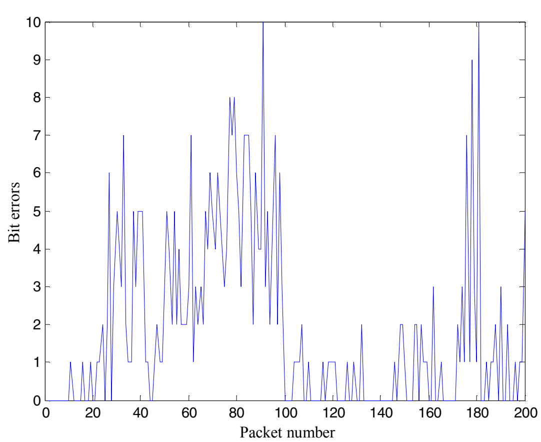

Fig. 14. Bit errors observed in 200 packets of 255 bytes

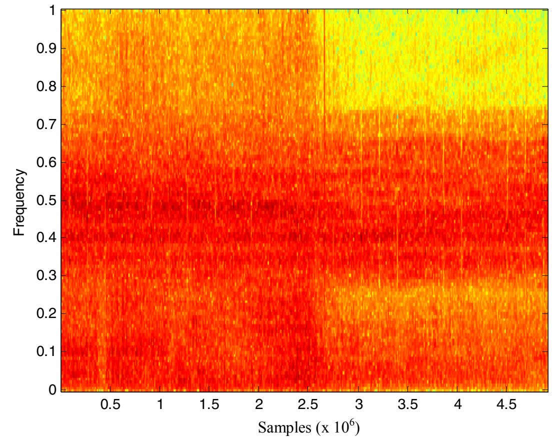

Fig. 15. Spectrogram view of received signal

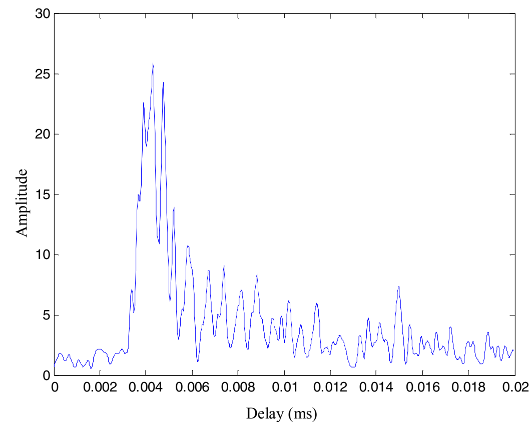

Fig. 16. Example channel impulse response for Tyne Estuary

Fig. 13-16 show the results from the transmission of 200 packets through the Tyne Estuary over a distance of 1.6km and approximately 10m channel depth. As shown in Fig. 16, this channel is characterised by a large number of multipath arrivals spanning at least 15ms. Furthermore this is a busy shipping channel with large vessels frequently passing at speed, leading to periods of very low SNR. The spectrogram of Fig. 15 shows how the first half of this recording is affected by broadband noise from a vessel. The impact of this is visible in Fig. 13 where the output signal to interference + noise ratio (SINR) is plotted over the 200 packets. Fig. 14 shows the number of errors measured in each packet which also deteriorates with the ship noise. However despite the severe multipath and noise, the receiver maintains a sufficiently low error rate for the RS decoder to deliver all 200 packets error free.

Another experiment was carried out at various ranges up to 300m in the same concrete lined dock as the USBL experiments shown in Fig. 9-10. Fig. 17 shows a typical channel impulse response for transmission over a distance of 100m. This shows a plethora of reflections resulting in time spread up to at least 80 ms of delay. Such long delays would be almost impossible to deal with by equalisation techniques and would necessitate extremely long symbols if conventional DSSS was employed. Fig. 18 shows the I-Q constellation for the received chips (after the linear equaliser) and the symbol values after de-spreading. The de-spreading process increases the effective SINR by approximately 7-8 dB. The correlation of an 8 chip sequence would be expected to yield 9dB of gain on average but the reduction is explained by the non-ideal correlation properties of the short segments of longer codes. However this slightly degraded processing gain can be guaranteed for very long multipath time spread rather than being limited by the symbol length.

The receiver is able to achieve a mean BER of $<10^{-2}$ before decoding and again the RS decoder is able to produce hundreds of consecutive error free packets in these channel conditions. In the same channel, further transmissions were made with rapid and erratic motion introduced on the transmitting unit to simulate the intended vehicle platforms/divers. The effectiveness of the closed-loop Doppler correction algorithm was clearly demonstrated with 96% of packets decoded compared to only 27% with this correction algorithm disabled. Fig. 19 shows an example of the equivalent velocity estimated by the closed loop Doppler correction algorithm. In this example the algorithm has successfully corrected for acceleration of approximately $-2m/s^2$, in the first half of the packet, followed by a change to positive acceleration. Without this estimation and consequent resampling of the received chips, the receiver loses synchronisation and the packet fails. Likewise a block Doppler correction, assuming a fixed velocity throughout the packet, is not sufficient to successfully receive the packet.

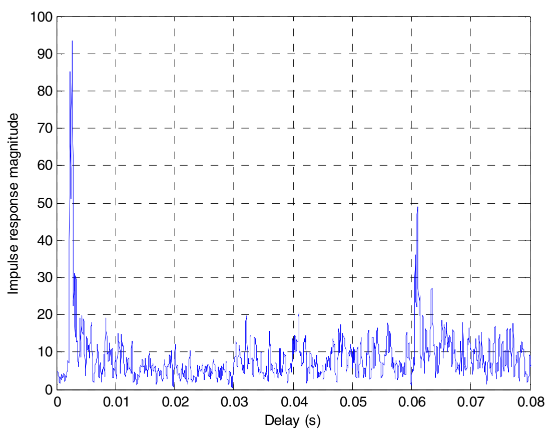

Fig. 17. Typical impulse response of 100m concrete dock channel

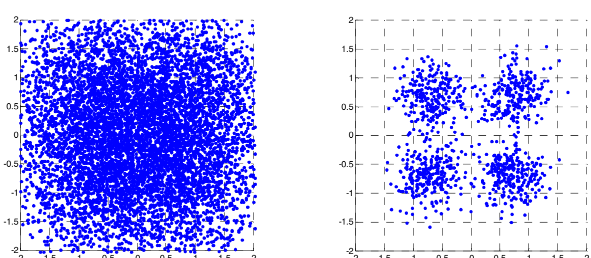

Fig. 18. I-Q constellations for chips (left) and de-spread symbols (right)

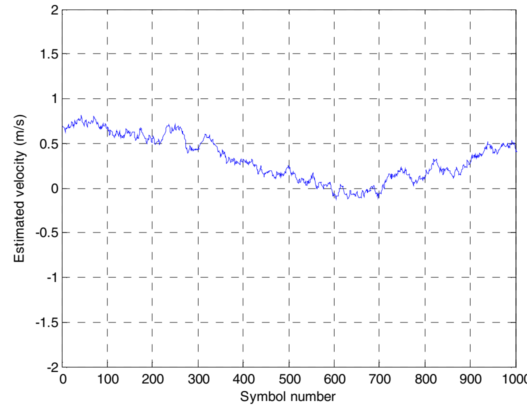

Fig. 19. Equivalent velocity from Doppler estimation algorithm

IV. Conclusions and Future Work

The Seatrac hardware platform and initial software algorithms have produced very promising results during testing in a variety of challenging environments. The CADDY project consortium are now using the devices to provide the communication and navigation for experiments in diver, AUV and ASV cooperation and feedback on performance to date is very positive. The devices are now in production by Blueprint Subsea and commercially available.

The 100bps LFM based transmission scheme has proven extremely reliable in all tests up to 1.5km range including very severe multipath channels. Positioning using the miniature USBL array has been shown to offer repeatability (standard deviation) of approximately 1.5% of range which is well within the requirements of the project. As expected this is dominated by variance in azimuth/elevation angle (~0.8 degrees) rather than range (<20cm repeatability). Accuracy and repeatability are expected to improve significantly in production due to reduced tolerances in array dimensions and analogue electronics. Work is also ongoing to investigate further algorithm enhancements to reduce the impact of imperfect array matching.

The higher data rate DSSS scheme has performed extremely well in trials to date and appears to be able to offer similar reliability to the 100bps scheme in severe channels. The approach of spreading symbols with segments of a much longer pseudorandom spreading sequence is offers a consistent reduction in ISI, for almost unlimited multipath delay spread, reducing error rates to a level that can be corrected by a modest coding overhead (~25%). The computational complexity of this scheme is modest and within the capability of the same hardware platform. Work is ongoing to implement this on the Seatrac devices to provide an effective throughput of 1.4kbits/s, whilst maintaining simultaneous USBL positioning. This will enable more data intensive missions for the CADDY system. Recent experiments in the North Sea, with signals in the 8-16kHz band, have shown that the same scheme can provide very reliable communication over ranges of up to 5km using source levels of no more than 180dB re 1µPa @ 1m. Future work will look at developing this system for long range telemetry networks.

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