Multi-Octave High-Frequency Hydro-Acoustic Communication

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***Abstract*—Underwater communication remains beset by a range of problems that stem from the inability of radio waves to propagate well through water. Although low frequency acoustic signals propagate well in water, the available bandwidth is limited. High acoustic frequencies can be used, although they do not propagate very far. This paper reports on high-frequency underwater communication trials using signals where the signal bandwidth is of the order of a decade. Even in open water tests, the received signals appear to be well behaved.**

Keywords—underwater communication, hydro-acoustic, high-frequency.

I. INTRODUCTION

The ocean covers over two-thirds of the Earth's surface, yet undersea communication remains very limited, both in node density and data rate. In part this is a result of our inability to use radio communication effectively through seawater. Acoustic signal can propagate to reasonable ranges, but the available frequencies reduce as a function of increasing range. Most undersea communication systems are designed for link ranges on the order of kilometers, limiting the upper frequency to some tens of kilohertz. Signal equalisation over such channels is possible, but difficult, and in any case the link capacity is constrained by the limited signal bandwidth available.

High capacity undersea networks remain elusive, yet it is apparent that high frequency acoustic communication would offer substantially increased bandwidth, albeit at the cost of link distance [1]. However use of the high-frequency channel has not been widely demonstrated. The high-frequency channel should differ from the complex propagation environment experienced at lower frequencies because of its shorter range. The shorter range limits the number of reflected paths available between the transmitter and receiver, so the received signal may be simpler to equalise.

OFDM is attractive as a low complexity signaling technique, making it ideal for the dense networks that could be built using high-frequency hydro-acoustic signaling. The open question is how OFDM will perform in the subject channel. Specifically how sensitive OFDM will be to the Doppler shifted multipath on a short-range high-frequency channel, and how the multi-octave bandwidth will impact on performance.

Modems have been reported working at high acoustic frequencies - specifically the Hermes modem is designed to operate in shallow harbour environments with substantial multipath [2]. Earlier work [3] does not seem to have produced practically useful results. OFDM offers a low complexity implementation, provided the received signal characteristics are suitable. This paper reports on ongoing works to ascertain the channel characteristics and specifically to demonstrate the suitability of OFDM for this channel. Initial open water test results are promising with modest equalisation requirements and raw bit error rates in the single digit range.

II. HIGH FREQUENCY UNDERWATER ACOUSTIC COMMUNICATION

Most contemporary underwater communication is carried at relatively low acoustic frequencies. A widely used example system carries 5 kbps on an acoustic signal in the range 7.2-12.5 kHz [4]. An early system [3] does not seem to have progressed beyond initial tests, while the Hermes modem [2] developed by Beaujean and Carlson has been widely reported, primarily in harbour environments with uplink data rates up to 87 kbps at carrier frequencies between 262-375 kHz.

The data rate achieved in a system is a combination of the number of symbols per second and the number of bits per symbol. In classical single carrier systems the number of bits per symbol is limited by the fidelity (SNR) of the received signal, so when the SNR is low a high data rate requires a high symbol rate. Given the limitations of the underwater acoustic channel, maintaining a high data rate with a single carrier means that the symbol rate has to be high. Assuming there is sufficient bandwidth to support the high symbol rate, the high symbol rate still presents difficulties for equalisation, as the Inter-Symbol Interference (ISI) can extend over many symbols. The equalisation problem can be simplified by replacing a single carrier modulation scheme with an multiple carrier system. Each carrier has a lower symbol rate, with a low number of bits per symbol, yet the aggregate throughput can be high as a result of using many parallel channels stacked in frequency. Unfortunately, if we manage each carrier individually, the packing density of carriers is limited by the requirement to maintain isolation between adjacent carriers. OFDM has been widely implemented as a means of obtaining a high

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carrier density, while managing cross-talk between carriers which would otherwise result in Inter-Carrier Interference (ICI). The subcarrier spacing in an OFDM signal is the inverse of the symbol duration, making each subcarrier orthogonal. Each symbol in an OFDM system is separated in time by a sufficiently large time duration to ensure that any significant multi-path arrivals do not interfere with the next symbol, thus there is no or negligible ISI. The energy arriving on the multiple paths does however affect the amplitude and phase of the signal as detected at the receiver. The reception system however requires only that the amplitude and phase of each subcarrier is corrected for this effect. Hence, pilot signals or training sequences are included in the transmitted signal to allow the receiver to estimate the phase and amplitude shifts imposed by the channel on each subcarrier.

The duration of each symbol is related to the likely time spread of multipath arrivals in the channel. As the speed of sound in water is relatively low - around 1500m/s - the multipath signals generally arrive over a period of several, or many, milliseconds. After allowing for a reasonable design margins and efficiency, the symbol period is often of the order of 10 ms. The subcarrier spacing is the inverse of the symbol duration, meaning that subcarriers are spaced apart by the order of 100 Hz. However any frequency shift as a result of Doppler or clock drift will mean that the subcarriers are no longer orthogonal, and ICI will result. It is for this reason that OFDM systems are sensitive to Doppler shifts.

When the bandwidth of the OFDM is small relative to the subcarrier frequency, any frequency offsets can be removed in the frequency domain, as in a narrowband system phase is a good proxy for time. However in broadband systems, the Doppler and clock offsets must be corrected in the time domain. This correction however is not simple, since it requires firstly that the timebase dilation or contraction be estimated with sufficient precision, and secondly that the signal be resampled at the required rate with low distortion. The computational cost of correcting for Doppler and clock errors can easily dwarf the subsequent computational cost of decoding the OFDM signal. This is in contrast to terrestrial radio systems where a key advantage of OFDM is its computational simplicity at the receiver.

The multipath arrivals can be modeled by ray tracing, where the uncertainties are the reflection angles from the non-flat ocean surface and bottom, and the reflection coefficients of said boundaries. In deeper water, refraction from the fast-deep path, and possible stratification of the water column add to the problem. A separate issue is the Doppler shift on each arrival. At first approximation this can be estimated from the rate of change in the length of each path, however ray tracing is normally performed on the assumption that the refractive index of the water is either constant within each layer, or varies in some smooth fashion. These effects may limit the signal fidelity, Doppler detection and correction strategy or optimal symbol and cyclic-prefix/zero-padding regime to be used on a given channel.

Physical measurements are necessary to support development of a robust theoretical and practical treatment of these issues, with the additional benefit of advancing the capability of equipment that can later be used to build practical systems to provide high data-rate communications for user applications.

III. TEST SYSTEM AND CONCEPT

The measurements described here are taken with a test arrangement similar to that described in [5]. The key changes have been that the transducer has been replaced by a ring transducer to minimise the multi-path issues we were experiencing with the reflector arrangement, the Cyclone III has been replaced by a Spartan-3A, which reads wave files from a micro-SD card. At present we produce the wave file in Matlab, at a sample rate of 4Msps, which the FPGA plays back via a DAC, into the power amplifier and transducer. The playback of the wave file is triggered by a one Pulse Per Second (1PPS) signal from a GPS receiver floating on the water surface above the node. This allows transmissions and signal collection (reception) to be synchronised. The synchronisation allows the signal time of flight to be measured with accuracy on the order of one microsecond, and thus the range between transmitter and receiver to be estimated with high accuracy - the propagation speed of sound in water being the largest source of uncertainty.

The testing encompasses multiple iterations through a graduated testing regime. Each test cycle begins with a Matlab simulation of the signal and signal decoding. The test signal is then turned into a wave file for transfer to the DSP modem hardware. For testing purposes the DSP modem hardware transmits a wave file from micro-SD card at regular intervals. The same system can also record digitised ultrasonic signals to micro-SD card for later analysis. A benchtop test through the analog interface is then undertaken, and the recorded signal is decoded in Matlab. The hardware is then packaged into waterproof housings and tested in a 25 kl diameter water tank, with the recorded signal again decoded in Matlab. Finally the assembled transmitters are deployed from a boat in a lake and recordings from the boat. A range of link distances and motion levels are recorded.

The recorded signals are then post-processed using the pre-programmed receiver algorithm in Matlab. Each processing run produces not only bit error rates, but maps all bit errors to subcarrier and symbol. The processing also stores the calculated equaliser values. The angle of the equaliser (single tap) for each subcarrier and symbol produces a very useful visualisation of the stability of the channel - and hence the potential utility of OFDM.

IV. FULL BROADBAND TEST

Initial tests were performed with an OFDM waveform that placed subcarriers across the entire band from 100kHz to 1MHz. The purpose of this waveform was to observe channel behavior across the entire band covered, and also to confirm the end-to-end link budget for each subcarrier, so that the most efficient can be selected for future trials. The subcarrier efficiency is driven primarily by the transducer response and the frequency dependant absorption rate of acoustic signals in water. The subcarrier details are: 4Msps sample rate, symbol period 65536 samples (16.4 ms), cyclic prefix 8000 samples, subcarrier modulation BPSK subcarriers used: 1638 to 16384 inclusive, packet preamble 80,000 sample length linear chirp from 200 to 100 kHz, 41 symbols per packet, packet postamble 80,000 sample length 1 MHz to 100 kHz downchirp.

In Figure 1 the equaliser angle corrections per subcarrier for the lowest octave of the transmitted signal are plotted. We see that the dominant effect is a time-base change, which has double the effect on phase rate at 200kHz as it does at 100kHz.

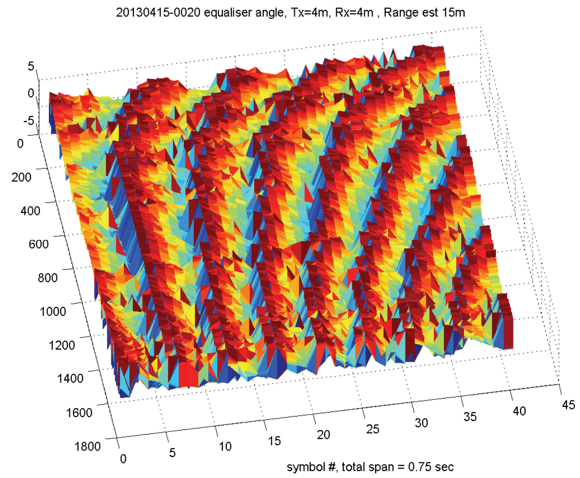

Fig. 1. Sample Equaliser angles from free-floating lake test (100-200 kHz)

Examining other recordings shows other effects, such as in Figure 2, where the lowest 1000 subcarriers (100-161kHz) from a similar free-floating lake test are shown.

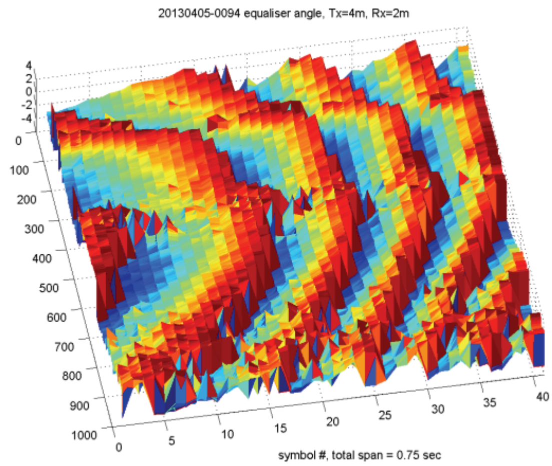

Fig. 2. Sample Equaliser angles from free-floating lake test (100-161 kHz)

At higher frequencies we tend to see a poorer SNR due to a combination of transducer responsivity and signal absorption. The rate of phase change due to the Doppler effect is also increased due to the shorter wavelength of the signal. This is shown in Figure 3, which plots the equaliser angle for the range 344-405 kHz.

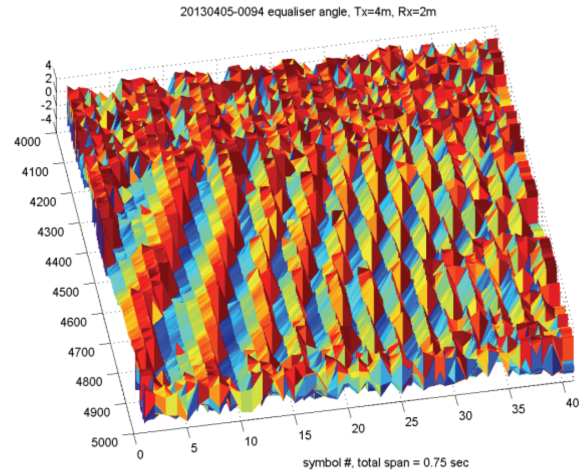

Fig. 3. Sample Equaliser angles from free-floating lake test (344-405 kHz)

Based on results from this trial, we refined the test technique and hardware to focus on a new ring-shaped transducer which eliminated some of the difficulties we experienced with the reflector system. The new arrangement also improved the signal level, which improved the Signal-to-Noise Ratio or reception range of the signal.

V. Dual Band Test

Firstly we confirmed that the new transducer was compatible with the remainder of the system, and performed an end-to-end test with the 100 k-1 MHz OFDM waveform in the indoor 25kl test tank. The equaliser plot from one of those test runs is shown in Figure 4.

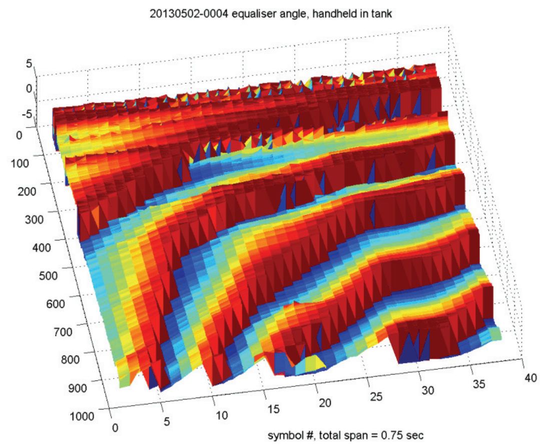

Fig. 4. Sample Equaliser angles from new transducer tank test (100k-1 MHz)

The transducer response has two strong frequency regions, to which we tailored the OFDM signal for a later set of lake tests. The OFDM waveform in both bands is created synchronously at baseband, we simply populate the subcarriers that lie within the two bands we intend to transmit on. The OFDM waveform created for the later trial reported here placed subcarriers from 90-120kHz and 525-825kHz. These bands were selected based on the response of the transducer. The advantage of limiting the transmission to these bands is that the signal-to-noise ratio (SNR) was improved compared to transmitting over the entire band. The subcarrier details are: 4Msps sample rate, symbol period 65536 samples (16.4 ms), cyclic prefix 32768 samples, subcarrier modulation BPSK, subcarriers used: 1475 to 1966 and 8602 to 13517 inclusive, symbols per packet 35, packet preamble was an 80,000 sample linear chirp from 525 to 825 kHz, there was no packet postamble.

The achieved range of this new transducer and waveform combination was tested by firstly measuring the average carrier plus noise level in each band at varying distances from the transmitter. These levels are shown in Figure 5.

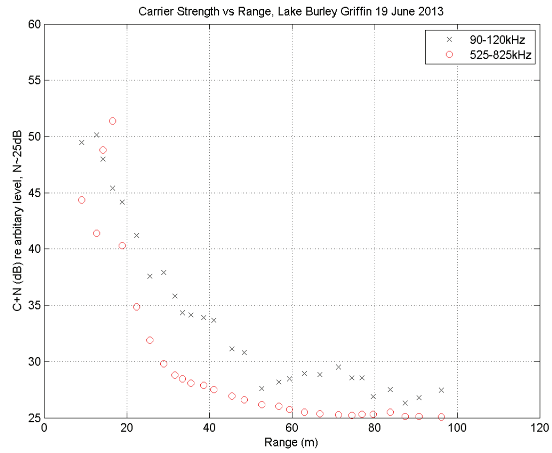

Fig. 5. Signal levels from free-floating lake test

The optimum Doppler correction was found by searching the Doppler space until the minimum BER was found. This method of deducing the optimal Doppler compensation is not intended for operational system, where methods based on null subcarriers would be more suited. In this trial we chose to fully populate the subcarriers, and select during post-processing which were (known) pilot signals and which were (unknown) data.

Although we refer to this effect as Doppler, it cannot be treated as a uniform frequency shift, because the narrowband assumption does not hold. Instead we explicitly adjust for the change in the time base by either adding or removing samples from the stream of values from the ADC. Removal of samples involves deleting evenly spaced samples symmetrically around the centre of the symbol period, addition of samples is similar, and just repeats one of the neighbouring samples. Given the sample rate of 4Msps, the Doppler steps in Figure 5 correspond to single samples in the 65536 samples per symbol of the recordings. Each sample of time offset per symbol period corresponds to:

$$2^{-16} \times 1500 \text{ m/s} = 0.023\text{m/s (0.044 knots)}$$

of relative velocity.

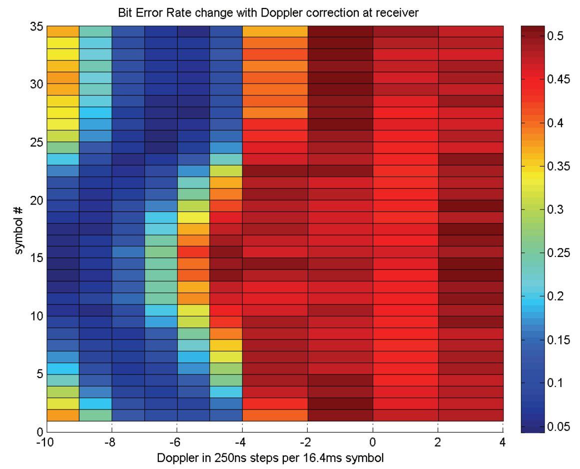

Fig. 6. Doppler for sample packet (525-825 kHz) from free-floating lake test

As an initial indication of performance, we plot the Bit Error Rate (BER), without any channel coding for each of the two bands in Figure 7. These BERs are calculated using an aggregate of every transmitted sub-carrier and symbol in our 1 second wave file, or a total of 16.8 and 168kbits respectively for the low and high bands. Investigations into the cause of the poor BER of the 90-120kHz signal are continuing.

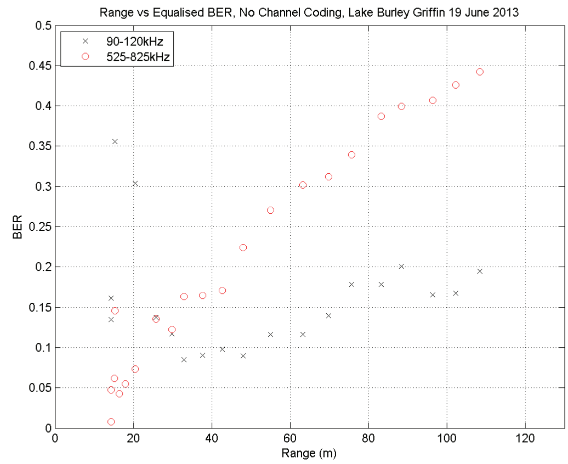

Fig. 7. Bit Error Rates from free-floating lake test

VI. Conclusion and Further Work

This paper has presented initial test results of a high-frequency multi-octave underwater acoustic communication system in open water conditions.

Work is in progress to rectify transducer and power limitations to provide modest improvements in range, and to remedy the poor bit error rate of the 90-120kHz signal.

VII. References

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