Poster Abstract: OFDM in Underwater Channels

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I. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is a wideband modulation scheme that has recently gained attention for underwater acoustic communications. The benefits of OFDM include its ability to overcome long channel delay spreads through the use of a guard interval, its ability to transform a frequency selective channel into multiple frequency non-selective channels, and its relatively easy implementation through the use of the fast fourier transform and its inverse.

However, OFDM has several distinct challenges in the underwater channel environment. The underwater channel is known to be highly frequency selective with large delay and Doppler spreading as well as fast time variance. The frequency selectivity requires accurate estimation of the channel transfer function in order to recover the transmitted symbols. Large delay spreading requires a longer guard interval, decreasing the data rate. Finally, Doppler spreading and fast time variations will introduce added noise at the demodulator due to inter-chip interference (ICI) and inaccurate channel estimation.

In this work in progress poster, we will show results of an experiment using zero padded (ZP) OFDM where good performance was achieved at ranges of 250m to 4km. The results will show that, counter-intuitively, the worst performance was achieved at 250m. The results highlight the sensitivity of the OFDM parameters to the specific conditions of the underwater channel.

II. OFDM Signal Model and Channel

We begin with a brief mathematical description of OFDM; a more thorough analysis is available from [1] [2]. The bandpass discrete time samples of the m-th transmitted signal are given as:

$$x_m(l) = \frac{1}{\sqrt{N_f}} \sum_{k=-\frac{N_f}{2}}^{\frac{N_f}{2}-1} X[m,k] e^{(j2\pi \frac{lk}{N_f})} g(l) \tag{1}$$

where m is the OFDM symbol index, l is the sampling index, N_f is the number of subcarriers, $X[m,k]$ is the submodulated symbol at the k-th orthogonal frequency, and $g(l)$ is a pulse shape that equals 1 for $0 \leq l < N_f$ and 0 otherwise. The total time required to transmit the OFDM symbol is $T = (N_f + N_g)T_s$ where N_g is the number of samples in the guard interval and T_s is the sampling period.

We model the channel as a tap delay line with N taps spaced at increments of the sampling interval T_s and, without loss of generality, assume that the delay of the first tap is zero. Neglecting the noise term and assuming perfect timing acquisition and no frequency offset, the received bandpass discrete time samples are:

$$\begin{aligned} r_m(l) &= \sum_{n=0}^{N-1} h_n(m,l) x_m(l-n) \\ &+ \sum_{y \neq 0} \sum_{n=0}^{N-1} h_n(m,l) x_{m-y}(l - n + (N_g + N_f)y) \end{aligned} \tag{2}$$

$$h_n(m,l) = \alpha_n e^{(j2\pi f_{Dn}[mT + lT_s])}$$

In (2) $h_n(m,l)$ is the n-th tap of the channel impulse response at time $(mT + lT_s)$ with complex gain α_n and Doppler f_{Dn}. The second term in (2) is the ISI, and is 0 if the guard interval is greater than or equal to the channel delay spread ($N_g \geq N$).

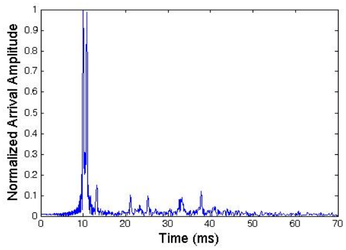
In order to demodulate the signal, the receiver adds the last N_g received samples of $x_m(l)$ to the beginning of the received signal, which transforms the linear convolution of the channel into a circular convolution. Channel estimation is achieved by sending known pilot signals as in [1].

Two aspects of the channel impulse response that will greatly affect the performance of the system are the length of the channel impulse response and the Doppler frequency. In order to avoid ISI (which acts as increased noise), the guard interval must be as long as the channel impulse response. Thus a longer channel impulse response will decrease the data rate. Frequency spreading will cause ICI by spreading the frequency content of adjacent subcarriers into one another, causing a loss of orthogonality. A way to mitigate this effect is to make the subcarriers wider as in [3]; however, this too lowers the achievable OFDM data rate.

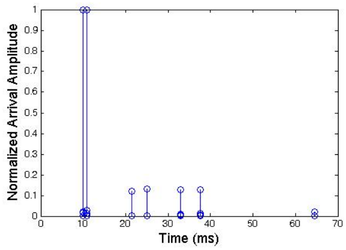
In the next section we give experimental results that directly show the effect of channel impulses beyond the guard interval.

III. Experimental Results

The experiment was conducted on Lake Washington in Seattle in January 2008. The depth of the water column was 60m, the sound speed profile was approximately uniform with depth, and there was very little wind or surface agitation. The bottom of Lake Washington is characterized as 'silty clay,'

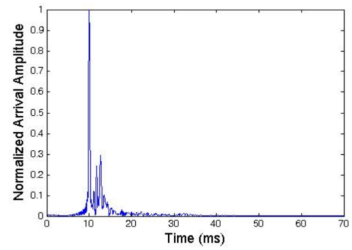


(a)

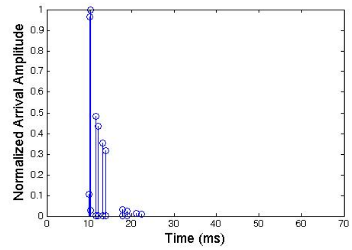


(b)

Fig. 1. Channel Impulse Response at 250m from data (a) and Bellhop (b).

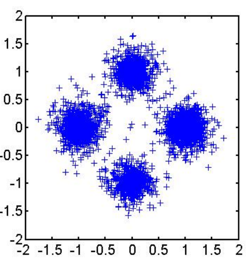


(a)

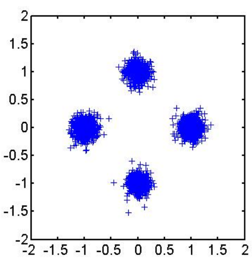


(b)

Fig. 2. Channel Impulse Response at 2km from data (a) and Bellhop (b).



(a)



(b)

Fig. 3. Output scatter plots at 250m (a) and 2km (b).

which acts to absorb signal energy and reduce multipath. The combination of low wind and surface agitation (implying low Doppler spread) and the muddy bottom of Lake Washington make this a very ideal acoustic channel for OFDM.

Signals were transmitted from a single hydrophone at approximately 30 meters depth from the R/V Melville, and were received at the R/V Henderson by a 4 element array with 8m spacing between elements that was centered at approximately 20m depth. The OFDM signal bandwidth was 4kHz, and a time domain raised cosine pulse shape with a rolloff factor of 0.4 was applied. The carrier frequency was 12 kHz, and the transmit power was 180 dB re 1uPa. There were 1024 subcarriers modulated using QPSK and Reed-Soloman encoding. The guard interval was set to 10ms. The raw data rate was 2012 bps, and the rate after coding was 939 bps.

The channel impulse responses at 250m and 2km for the top hydrophone are shown in Figs. 1 and 2. As a comparison, impulse responses generated by Bellhop [4], a Gaussian Ray tracing program, with environmental characteristics that match Lake Washington are also added, which show great similarity. We can see that at 250m significant channel impulses occur beyond the guard period of 10ms. However, at 2km, all the impulses are contained within 10ms. Scatter plots of the results are shown in Fig. 3. As expected, increased noise is shown in the output at 250m. At 250 meters, 16 of 3840 bits were received in error before decoding; at 2km no bits were received in error. All bits were received error free at both ranges after decoding.

IV. Conclusions and Future Work

Our results give an example of better OFDM performance at further ranges due to specific underwater channel conditions. This implies that the data rate is not a monotonically decreasing function of range. Further research efforts are required to determine in what underwater channel conditions OFDM is a suitable candidate for transmission, specifically with respect to channel time and frequency spread. The similarity between the Bellhop channel and the experimental channel shows potential in using such tools to predict system performance. Future work will focus on the effect of wind in adding Doppler spread to ray paths that reflect from the surface.

Acknowledgment

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References

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