Short Paper: OFDM in Deep Water Acoustic Channels with Extremely Long Delay Spread

Zhaohui Wang, Shengli Zhou
ECE Department
University of Connecticut
Storrs, CT 06269

Josko Catipovic
Naval Undersea Warfare Center
Newport, RI 02841

Jie Huang
ECE Department
University of Connecticut
Storrs, CT 06269

ABSTRACT

Deep water horizontal channels usually have very long delay spreads relative to shallow water channels. The delay spread can be several hundreds of milliseconds, which covers several blocks of orthogonal frequency division multiplexing (OFDM) transmissions, leading to severe inter-block-interference (IBI). There are usually two significant well-separated clusters, one from direct paths and the other from surface reflections. Viewing the signals arrived along the two clusters as from two virtual users, we develop a multiuser based OFDM receiver to address IBI, where both channel estimation and data detection algorithms are presented. This receiver can effectively combine signals from multiple senors with different delay spread structures, where each block is decoded in the presence of interference from multiple different blocks. Experimental data from the Atlantic Undersea Test and Evaluation Center (AUTEC) environment are used to validate the performance of the proposed receiver.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Communications Applications; C.3 [**Special-purpose and Application-based Systems**]: Signal Processing Systems

General Terms

Algorithms, Design, Experimentation, Measurement

Keywords

Zero-padded OFDM, long delay spread, joint sparse channel estimation, multiuser detection.

1. INTRODUCTION

Recently, multicarrier modulation has been actively investigated for underwater acoustic (UWA) communications. Example results of zero-padded orthogonal frequency division multiplexing (ZP-OFDM) in shallow water communications can be found in [1–3], which are based on the assumption that the guard interval is longer than the channel delay spread, such that there is no inter-block-interference (IBI) in the received signals.

In this paper, we consider the application of ZP-OFDM in deep water channels, where the delay spread can be on the order of hundreds of milliseconds. In this scenario, it is not wise to have the guard interval longer than the delay spread, as that would lead to significant rate reduction. Severe IBI thus occurs in the received signal, which can paralyze reliable data transmission if not addressed appropriately.

Observe that multiple paths in deep water channels are clustered with good separations. If the blocks received along different clusters are viewed as signals from different virtual users, a *multiuser* based receiver can be applied. The idea of using multiuser concept to handle the extremely long delay spread in deep water channels has been suggested in [4] for single carrier transmissions. In this paper, we utilize it to develop a receiver for block based OFDM transmissions. Rather than suppressing the signals from late arrivals, this receiver effectively combines the useful signals from both clusters to decode each OFDM block in the presence of interference of other blocks.

The rest of the paper is organized as follows. The channel characteristics and the signal design are introduced in Section 2. The proposed receiver is presented in Section 3. Section 4 provides the experimental results, and in Section 5 we draw conclusions.

2. SYSTEM DESCRIPTION

2.1 Channel Characteristics

Deep water acoustic channels usually consist of multiple well-separated clusters, with each cluster including multiple paths. These clusters are formed by direct transmissions and surface/bottom reflections, among which direct transmissions and the first surface reflections constitute two dominant ones. With the depth h of the transmitter and the receiver, and the distance d in between, the difference of time-of-arrivals of the two clusters can be roughly calculated as $(\sqrt{4h^2+d^2}-d)/c$. Taking $h = 2$ km, $d = 5$ km and sound speed $c = 1500$ m/s as an example, the inter-cluster arrival time is around 930 ms.

Fig. 1 shows correlation results of the data recorded in one experiment using the linear frequency modulation (LFM) signals. The first and the second clusters correspond to the direct paths and the surface reflections respectively. We find that these two clusters are well separated, and the inter-

WUWNet'10, Sept. 30 - Oct. 1, 2010, Woods Hole, Massachusetts, USA

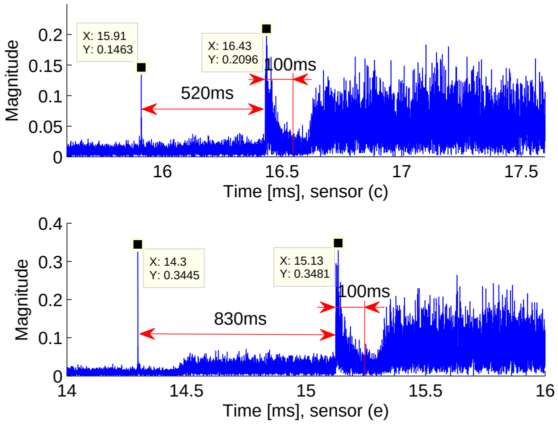

Figure 1: LFM correlation results.

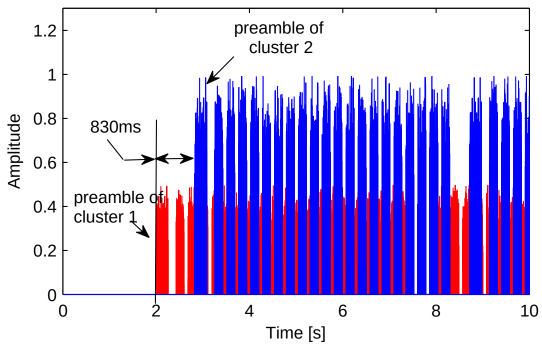

Figure 2: Illustration of IBI in ZP-OFDM transmissions over a channel with two clusters.

cluster arrival time is quite different on different sensors, which are separately miles away. Besides the extremely long delay spread between the two clusters, the delay spread of the second cluster is also much longer than the delay spread in shallow water channels.

2.2 Signal Design

We consider a zero-padded OFDM transmission in deep water channels. The transmitted bits are first encoded with a nonbinary LDPC code. After mapping coded symbols into QPSK symbols, pilot symbols are multiplexed with data symbols for channel estimation. OFDM blocks can then be generated by the inverse discrete Fourier transform followed by baseband-to-passband upshifting. Guard interval is inserted between OFDM blocks to avoid IBI. In general, the time duration of guard interval is required to be no less than the delay spread of the channel.

Consider the delay spread of deep water channels. The extremely long guard interval could result in significant data rate reduction. We thus would like to maintain the typical parameter setting used in shallow water communications as shown in Table 1, and come up with a new receiver to address the IBI problem. An illustration of the IBI for a two-clustered channel is shown in Fig. 2.

Table 1: ZP-OFDM Parameters

Sampling frequency	$f_s = 96$ kHz
Center frequency	$f_c = 11$ kHz
Signal bandwidth	$B = 6$ kHz
Number of subcarriers	$K = 1024$
Subcarrier spacing	$B/K = 5.86$ Hz
OFDM symbol duration	$T = 170.67$ ms
Guard interval	$T_g = 85.33$ ms

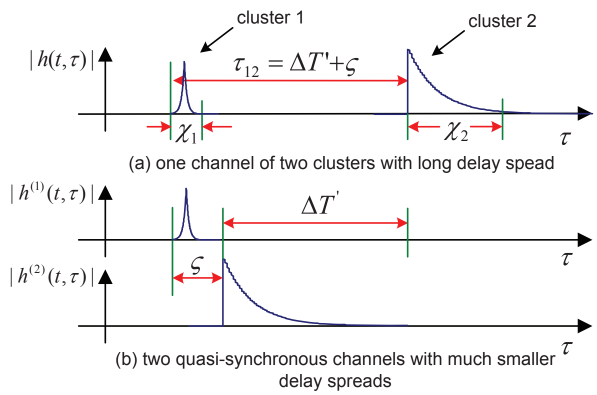

Figure 3: Illustration of the *multiuser* concept.

3. PROPOSED RECEIVER

The proposed receiver is based on the property of well-separated multiple clusters. Assume two significant clusters in the channel. Define χ_1 and χ_2 as the delay spreads within the two clusters respectively, and τ_{12} the difference of time-of-arrivals of the two clusters. Define an integer Δ and a residual $|\varsigma| < T'/2$. The delay spread τ_{12} can be decomposed as

$$\tau_{12} = \Delta T' + \varsigma, \tag{1}$$

where $T' = T + T_g$ is the ZP-OFDM block duration; see the illustration in Fig. 3(a). If the two clusters are viewed as two independent channels, the channel impulse response in Fig. 3(a) can be expressed as the summation of the impulse responses of these two channels in Fig. 3 (b), such that

$$h(t,\tau) = h^{(1)}(t,\tau) + h^{(2)}(t,\tau - \Delta T'). \tag{2}$$

The received signal at a certain time slot is therefore the summation of the signals of *user 1* and *user 2* transmitted over two individual channels. Note that although the transmitted signals of the two users are the same, transmission of the second user is roughly Δ blocks delayed relative to the transmission of the first user.

We adopt the following assumption that $(\varsigma + \chi_2) \leqslant T_g$ when $\varsigma \geqslant 0$ or $\min\{\chi_2, \chi_1 - \varsigma\} \leqslant T_g$ when $\varsigma < 0$. In this way, the received signals can be effectively partitioned into individual blocks. After applying FFT on each partitioned block, the frequency measurements of the $(b+\Delta)$th received block can be expressed as

$$\mathbf{z}_{b+\Delta} = \begin{pmatrix} \mathbf{H}^{(2)} & \mathbf{H}^{(1)} \end{pmatrix} \begin{pmatrix} \mathbf{s}_b \\ \mathbf{s}_{b+\Delta} \end{pmatrix} + \mathbf{v}_{b+\Delta}. \tag{3}$$

where $\mathbf{H}^{(1)}$ and $\mathbf{H}^{(2)}$ denote the channel mixing matrices corresponding to the first and the second cluster respectively, and $\mathbf{s}_b$ and $\mathbf{s}_{b+\Delta}$ denote the transmitted symbols of

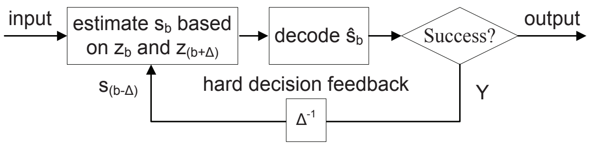

Figure 4: Hard decision-feedback multiuser receiver in deep water channels with inter-block-interference.

the bth and $(b+\Delta)$th block. Detailed formulation of the channel mixing matrix can be found in [3]. To explicitly consider the inter-carrier-interference (ICI) due to Doppler effects, we here assume $\mathbf{H}^{(i)}(i=1,2)$ as a banded channel matrix with the main diagonal and four off-diagonals [3].

3.1 Joint Sparse Channel Estimation

Estimation of all the channel mixing matrices in (3) is required for symbol detection. Given the residual delay spread ς, one can find that what we are addressing is a quasi-synchronous two-user channel estimation problem. Combining the ideas from [3] which deals with the ICI-aware channel estimation for the single transmitter case and [2] which deals with the ICI-ignorant channel estimation for the multiple-transmitters case, the joint ICI-aware sparse channel estimation can be applied on each block individually. Detailed description about sparse channel estimation can be found in [2] and [3]. We skip them here due to the space limitation.

3.2 *Multiuser* Demodulation

Different from channel estimation, data detection of one transmitted block can use multiple received blocks and blocks from multiple receivers, which leads to a multiuser problem with more than two virtual users. Note that since the data detection depends on multiple received blocks, the decoding operation can only be performed until the transmitted block passing along the last cluster has arrived.

3.2.1 Joint detection

We start the formulation using one sensor. Eq. (3) suggests that $\mathbf{s}_b$ shows up in both of the bth and $(b+\Delta)$th received block. Stacking the two received blocks yields

$$\underbrace{\begin{pmatrix}\mathbf{z}_b\\ \mathbf{z}_{b+\Delta}\end{pmatrix}}_{:=\mathbf{z}}=\underbrace{\begin{pmatrix}\mathbf{H}_b^{(2)} & \mathbf{H}_b^{(1)} & \mathbf{0}\\ \mathbf{0} & \mathbf{H}_{b+\Delta}^{(2)} & \mathbf{H}_{b+\Delta}^{(1)}\end{pmatrix}}_{:=\mathbf{H}}\underbrace{\begin{pmatrix}\mathbf{s}_{b-\Delta}\\ \mathbf{s}_b\\ \mathbf{s}_{b+\Delta}\end{pmatrix}}_{:=\mathbf{s}}+\underbrace{\begin{pmatrix}\mathbf{v}_b\\ \mathbf{v}_{b+\Delta}\end{pmatrix}}_{:=\mathbf{v}}. \tag{4}$$

One can view (4) as a problem that the transmitted blocks from three virtual users collide with each other. An MMSE equalizer can be applied as

$$\hat{\mathbf{s}}=\left(\mathbf{H}^H\mathbf{H}+N_0\mathbf{I}\right)^{-1}\mathbf{H}^H\mathbf{z}, \tag{5}$$

where N_0 denotes the noise variance. The computational complexity can be significantly reduced by exploiting the banded structure of the channel mixing matrices. Estimation $\hat{\mathbf{s}}_b$ can then be extracted from $\hat{\mathbf{s}}$, while $\hat{\mathbf{s}}_{b-\Delta}$ and $\hat{\mathbf{s}}_{b+\Delta}$ are discarded.

3.2.2 Interference cancelation

One can find that if the transmitted blocks prior to the current block $\mathbf{s}_b$ have been successfully decoded, the prior blocks can be used to facilitate the estimation of $\mathbf{s}_b$. With the hard decision feedback strategy shown in Fig. 4, interference cancelation leads to

$$\begin{pmatrix}\mathbf{z}_b-\mathbf{H}_b^{(2)}\mathbf{s}_{b-\Delta}\\ \mathbf{z}_{b+\Delta}\end{pmatrix}=\begin{pmatrix}\mathbf{H}_b^{(1)} & \mathbf{0}\\ \mathbf{H}_{b+\Delta}^{(2)} & \mathbf{H}_{b+\Delta}^{(1)}\end{pmatrix}\begin{pmatrix}\mathbf{s}_b\\ \mathbf{s}_{b+\Delta}\end{pmatrix}+\begin{pmatrix}\mathbf{v}_b\\ \mathbf{v}_{b+\Delta}\end{pmatrix}, \tag{6}$$

based on which $\mathbf{s}_b$ can be estimated.

3.2.3 Combing sensors with similar delay structures

Signals from multiple sensors are usually available, while the cluster structure of each sensor depends on the geometries of the sensor and the transmitter. For data symbol detection, we would like to perform sensor-grouping according to their cluster structures.

For sensors within the same group, i.e., sensors with two clusters roughly separated with the same $\Delta T'$, the detection problem becomes a three-transmitter multiple-receiver problem [2]. The proposed receiver can be easily extended by stacking more observation vectors into $\mathbf{z}$ while keeping transmitted blocks $\mathbf{s}$ the same. Taking two sensors as an example, (4) becomes

$$\begin{pmatrix}\mathbf{z}_b^{(1)}\\ \mathbf{z}_{b+\Delta}^{(1)}\\ \mathbf{z}_b^{(2)}\\ \mathbf{z}_{b+\Delta}^{(2)}\end{pmatrix}=\begin{pmatrix}\mathbf{H}_b^{(1,2)} & \mathbf{H}_b^{(1,1)} & \mathbf{0}\\ \mathbf{0} & \mathbf{H}_{b+\Delta}^{(1,2)} & \mathbf{H}_{b+\Delta}^{(1,1)}\\ \mathbf{H}_b^{(2,2)} & \mathbf{H}_b^{(2,1)} & \mathbf{0}\\ \mathbf{0} & \mathbf{H}_{b+\Delta}^{(2,2)} & \mathbf{H}_{b+\Delta}^{(2,1)}\end{pmatrix}\begin{pmatrix}\mathbf{s}_{b-\Delta}\\ \mathbf{s}_b\\ \mathbf{s}_{b+\Delta}\end{pmatrix}+\begin{pmatrix}\mathbf{v}_b^{(1)}\\ \mathbf{v}_{b+\Delta}^{(1)}\\ \mathbf{v}_b^{(2)}\\ \mathbf{v}_{b+\Delta}^{(2)}\end{pmatrix}, \tag{7}$$

where $\mathbf{z}^{(i)}$ and $\mathbf{v}^{(i)}$ denote the frequency measurements and the ambient noise of the ith sensor, respectively, and $\mathbf{H}^{(i,j)}$ denotes the channel matrix corresponding to the jth cluster of the ith sensor. Joint detection or interference cancelation can then be applied on (7) to estimate the data symbols $\mathbf{s}_b$.

3.2.4 Combing sensors with different delay structures

The proposed receiver can be also extended to combine sensors from different groups, i.e., sensors with clusters separated by different $\Delta T'$. Take two sensors as an example. Define Δ_1 and Δ_2 as the integer block delays between the two clusters of the two sensors, respectively. The relevant measurements for $\mathbf{s}_b$ can be collected as

$$\begin{pmatrix}\mathbf{z}_b^{(1)}\\ \mathbf{z}_{b+\Delta_1}^{(1)}\\ \mathbf{z}_b^{(2)}\\ \mathbf{z}_{b+\Delta_2}^{(2)}\end{pmatrix}=\begin{pmatrix}\mathbf{v}_b^{(1)}\\ \mathbf{v}_{b+\Delta_1}^{(1)}\\ \mathbf{v}_b^{(2)}\\ \mathbf{v}_{b+\Delta_2}^{(2)}\end{pmatrix}+ \tag{8}$$

$$\begin{pmatrix}\mathbf{0} & \mathbf{H}_b^{(1,2)} & \mathbf{H}_b^{(1,1)} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{H}_{b+\Delta_1}^{(1,2)} & \mathbf{H}_{b+\Delta_1}^{(1,1)} & \mathbf{0}\\ \mathbf{H}_b^{(2,2)} & \mathbf{0} & \mathbf{H}_b^{(2,1)} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{H}_{b+\Delta_2}^{(2,2)} & \mathbf{0} & \mathbf{H}_{b+\Delta_2}^{(2,1)}\end{pmatrix}\begin{pmatrix}\mathbf{s}_{b-\Delta_2}\\ \mathbf{s}_{b-\Delta_1}\\ \mathbf{s}_b\\ \mathbf{s}_{b+\Delta_1}\\ \mathbf{s}_{b+\Delta_2}\end{pmatrix}.$$

Hence, five blocks collide with each other. An MMSE or zero-forcing (ZF) equalizer can then be applied to estimate the symbol vector $\mathbf{s}_b$.

Obviously, one can combine different sensor-groups to achieve better symbol detection performance. Let G denote the number of groups combined, and G_i the number of sensors of the ith group. After group combing, the detection problem has $(2G+1)$ blocks in $\mathbf{s}$ and $\sum_{i=1}^{G}(2G_i)$ blocks in $\mathbf{z}$, from which $\mathbf{s}_b$ can be estimated. Performance of the receiver with single group and multiple groups will be tested with the experimental data in the sequel.

Table 3: Decoding Results for Sensors with Two Clusters in the Experiment

Receiver type	Sensor-groups	$\|\mathcal{S}_P\|$	$\|\mathcal{S}_D\|$	LDPC rate	Uncoded BER	BLER	Date rate
Interference cancelation	group 1	672	256	1/3	0.160	0	255 B/(3s)
Interference cancelation	group 1, group 2	672	256	1/2	0.150	0	383 B/(3s)
Joint detection	group 1, group 2	672	256	1/3	0.118	0	255 B/(3s)

Table 2: Sensors Groups in the Experiment

Sensor	Group1			Group2	
	(a)	(b)	(c)	(d)	(e)
d (km)	7.6	7.5	6.2	3.82	3.81
τ_{12} (ms)	582	581	505	707	713
Δ	2	2	2	3	3
ς (ms)	70	69	-7	-61	-55
PSNR (dB)	6.7	6.1	6.0	6.2	5.9

d denotes the distance between the transmitter and receivers, and PSNR denotes the pilot-SNR of the received signal after FFT operation.

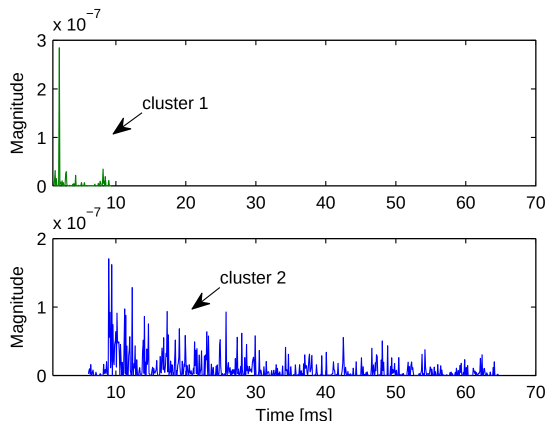

Figure 5: Channel estimation results at sensor (c).

4. EXPERIMENTAL RESULTS

This experiment was carried out in December 2008 by the Atlantic Undersea Test and Evaluation Center (AUTEC) around the Andros Island near the Tongue of the Ocean, Bahamas [5]. In the experiment, there is one transmitter and 95 receivers located in an area of size 30 km × 30 km, while we only focus on five receivers in this paper. The receivers are at least 4 km apart from each other. Depth of the transmitter and the receivers varies from 1.5 km to 2 km. Parameter settings of this experiment are shown in Table 1. Out of 1024 subcarriers, $|\mathcal{S}_P| = 672$ are evenly distributed pilot subcarriers, 96 are null subcarriers with half at the edges of signal band for signal band protection and half evenly spaced among the rest of $|\mathcal{S}_D| = 256$ data subcarriers for carrier-frequency-offset compensation. A nonbinary LDPC code and a QPSK constellation are used.

The five receivers can be divided into two groups depending on the block delays, as shown in Table 2. Fig. 1 shows examples of the LFM correlations at sensor c and sensor e. With the analysis in Section 3, our detection problem becomes a 2-user/6-receiver multiple-input multiple-output (MIMO) problem when one group is used, and a 5-user/10-receiver MIMO problem when two groups are combined.

One sample channel estimation is shown in Fig. 5. A ZF equalizer is used as the performance benchmark, and an MMSE equalizer can be applied as well. The decoding results averaged over 15 blocks are shown in Table 3, in which the data rate is calculated as

$$R = r_c \cdot \frac{|\mathcal{S}_D| \cdot \log_2 4}{T + T_g} \text{ bits/s}, \tag{9}$$

with r_c denoting the LDPC rate. The data rate can also be expressed as $\frac{3}{8}R$ Bytes/(3s), which is the unit used by the current AUTEC single carrier system with a typical package time duration of 3 seconds.

One can find that the proposed receiver works well in the presence of IBI in the received signal. The performance of group-combining is better than that of a single group. For the group-combining receiver, the performance of interference cancelation is better than that of the joint detection due to the utilization of the information of the prior blocks. With a careful signal design on the number of pilot subcarriers, higher data rate could be achieved.

5. CONCLUSIONS

In this paper, we presented one *multiuser* based receiver for ZP-OFDM in deep water acoustic channels with extremely long delay spread. To combat IBI, we exploited the property of well-separated multiple clusters and developed a multiuser receiver by viewing the collided block as the signal from individual *users*. We showed that this receiver can be easily extended to the scenario of multiple sensors with different cluster structures. Initial results in the AUTEC environment demonstrated the effectiveness of the receiver.

Acknowledgments

This work was supported by the ONR grants N00014-07-1-0805 (YIP), N00014-09-1-0704 (PECASE) and the NSF grant CNS-0721834.

6. REFERENCES

[1] B. Li, S. Zhou, M. Stojanovic, L. Freitag, and P. Willett, "Multicarrier communication over underwater acoustic channels with nonuniform Doppler shifts," *IEEE J. Ocean. Eng.*, vol. 33, no. 2, Apr. 2008.

[2] J. Huang, J.-Z. Huang, C. R. Berger, S. Zhou, and P. Willett, "Iterative sparse channel estimation and decoding for underwater MIMO-OFDM," in *Proc. of MTS/IEEE OCEANS Conf.*, Biloxi, MS, Oct. 2009.

[3] C. R. Berger, S. Zhou, J. Preisig, and P. Willett, "Sparse channel estimation for multicarrier underwater acoustic communication: From subspace methods to compressed sensing," *IEEE Trans. Signal Processing*, vol. 58, Mar. 2010.

[4] Z. Zvonar, D. Brady, and J. Catipovic, "An adaptive decentralized multiuser receiver for deep-water acoustic telemetry," *J. Acoust. Soc. Am.*, vol. 101, Apr. 1997.

[5] R. Hayford, D. Nagle, and J. Catipovic, "AUTEC Undersea Cellular Network," *Poster at WUWNet09*, Berkeley, California, Nov. 2009.