Receiver Comparisons on an OFDM Design for Doppler Spread Channels

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Abstract

Underwater acoustic channels induce large Doppler drifts that result in intercarrier interference (ICI) for OFDM transmissions. Assuming that after proper Doppler compensation the residual ICI is limited to only direct neighbors, we propose an OFDM signal design that decouples channel estimation and data demodulation. We investigate five receivers that are categorized into three groups: (i) two receivers that ignore the residual ICI, (ii) two receivers that are based on a basis expansion model (BEM) and pursue channel estimation independently along each basis, and (iii) one receiver that is based on a path-based model. The receiver performance is compared based on data from the GLINT experiment conducted south of the island Elba in the Mediterranean, July 2008, and the SPACE experiment conducted off the coast of Martha’s Vineyard, Massachusetts, October 2008. The receiver based on the path-based model and a basis pursuit (BP) algorithm achieves the best performance, followed by the ICI-ignorant and BEM versions of BP. The least-squares channel estimation performs the worst, especially in combination with the BEM. The BEM based receivers are often inferior to the ICI-ignorant counterparts, except for conditions with very large Doppler spread. This implies that there exists a trade-off between ICI compensation and the estimation accuracy of the much increased number of BEM parameters. On the contrary, the path-based channel model facilitates ICI compensation without increasing the number of model parameters, by exploiting the sparse representation in the joint delay-Doppler domain.

Index Terms

Underwater acoustic communication, inter-carrier interference, channel estimation, Basis Pursuit.

I. INTRODUCTION

Fast variation of underwater acoustic (UWA) channels introduces intercarrier interference (ICI) for underwater multicarrier transmissions. The receivers in [3], [4] are constructed assuming that all propagation paths have a similar path variation rate and the residual ICI can be ignored after proper Doppler compensation. On the other hand, basis expansion models (BEM) have been used to approximate doubly (time- and frequency-) selective UWA channels in [5]–[7] so that the ICI is limited to neighboring subcarriers.

In this paper, we assume that the residual ICI of an orthogonal frequency division multiplexing (OFDM) system is limited to only direct neighbors after proper Doppler compensation. We then propose an OFDM signal design that decouples channel estimation and data demodulation. Specifically, pilot and data subcarriers are separated by at least two null subcarriers so that
(presumably) they do not interfere with each other. For this system, we investigate five receivers that are categorized into three groups:

- Two receivers that ignore the residual ICI, where least-squares (LS) as in [3], and basis pursuit (BP) algorithms as in [8] are used for channel estimation based only on measurements on pilot subcarriers. The LS channel estimator assumes the channel to be non-sparse while BP is a compressive sensing algorithm [9], which is suitable for sparse channel estimation [8].

- Two receivers that are based on the basis expansion model, where channel estimation is done independently along each basis using either the LS or BP algorithm.

- One receiver that relies on a path-based model, where the BP algorithm explains the channel observations with a minimum number of entries from a joint delay/Doppler dictionary, as in [1], [8].

We compare the receiver performance using data recorded from the GLINT experiment, conducted in the Mediterranean, south of the island Elba, Italy, in July 2008, and the SPACE experiment, which was held for about two weeks off the coast of Martha’s Vineyard, Massachusetts, in Oct. 2008. For systems with a small size constellation, all receivers work well, but the performance differences among different receivers increase with the signal constellation size. The receiver based on the path-based model and the BP algorithm achieves the best performance across the board, followed by the ICI-ignorant and BEM versions of BP. The LS receivers perform the worst. An interesting observation is that the BEM based receivers only outperform the ICI-ignorant counterparts, when the Doppler spread is large. This reveals a tradeoff between the estimation accuracy of the increased number of BEM parameters and the ability to model and equalize ICI.

The study in this paper signifies the importance of using the least number of parameters (i.e., the degrees of freedom) to best approximate the channel dynamics. Ignoring the residual ICI, the sparse channel estimator reduces the number of unknowns $L$ in the LS estimator to $N_p$, where $N_p$ is the number of significant paths and $L$ is the maximum number of channel taps in baseband. The BEM based model captures the ICI from direct neighbors, but triples the number of unknowns. The path-based model captures the ICI without increasing the number of unknowns, by exploiting the sparsity in the joint delay-Doppler domain.
The rest of the paper is organized as follows. Section II presents the signal design and Section III describes the different types of considered receivers. Sections IV and V contain the performance results based on the GLINT’08 and SPACE’08 experiments respectively, while conclusions are drawn in Section VI.

II. THE PROPOSED SIGNAL DESIGN

Let $T$ denote the signal duration and $T_g$ the zero padding interval, leading to a total OFDM block duration of $T' = T + T_g$. Subcarriers are located at frequencies

$$f_k = f_c + k/T, \quad k = -K/2, \ldots, K/2 - 1,$$

(1)

where $f_c$ is the center frequency, $K$ is the total number of subcarriers. The subcarrier spacing is $1/T$ and the bandwidth is $B = K/T$.

Define $S_A$ and $S_N$ as the nonoverlapping sets of active and null subcarriers, respectively, that satisfy $S_A \cup S_N = \{-K/2, \ldots, K/2 - 1\}$. Let $s_k$ denote the symbol to be transmitted on the $k$th subcarrier. The transmitted signals in baseband and passband are respectively:

$$x(t) = \sum_{k \in S_A} s_k e^{j2\pi k t} q(t), \quad t \in [0, T'],$$

(2)

$$\tilde{x}(t) = \text{Re} \left\{ \sum_{k \in S_A} s_k e^{j2\pi f_c t} e^{j2\pi f_c t} \right\}, \quad t \in [0, T'] .$$

(3)

where $q(t)$ describes the zero-padding operation:

$$q(t) = \begin{cases} 1, & t \in [0, T]; \\ 0, & \text{otherwise}. \end{cases}$$

(4)

The signal design in [3] assumes that all propagation paths have a similar Doppler scale and the residual ICI can be ignored after proper Doppler compensation. Now we propose a
signal design based on the assumption that: *The residual ICI after proper Doppler compensation is limited to only direct neighbors.* Therefore, as long as each pilot subcarrier and any data subcarrier are separated by at least two null subcarriers, there is no spillover between the data and pilot subcarriers. This decouples channel estimation and data demodulation, enabling low complexity receiver processing; examples along this principle can be found in [10].

Specifically, we define an $8 \times 1$ subvector $s_m$ that contains one pilot symbol, $p_m$, and three data symbols, $d_m = [d_{m,1}, d_{m,2}, d_{m,3}]^T$ in the following way:

$$s_m = [0 \ p_m \ 0_{1\times 2} \ d_m^T \ 0]^T. \quad (5)$$

On each OFDM block, the symbol vector $s$ consists of $M = K/8$ subvectors so that

$$s = [s_1^T, ..., s_M^T]^T. \quad (6)$$

An illustration of the subcarrier allocation is shown in Fig. 1. We define the pilot index as

$$\{i_m\} = \{8(m-1) + 1\}, \quad m = 1, ..., M. \quad (7)$$

The the left and right neighbors of pilot subcarriers (which contain nulls) are $\{i_m^-\}$ and $\{i_m^+\}$, where $\{i_m^\pm\} = \{i_m \pm 1\}$.

### III. Receiver Descriptions

The receiver diagram is shown in Fig. 2. The received passband signal $\tilde{y}(t)$ may undergo a resampling operation to obtain $\tilde{z}(t)$. After down conversion and Doppler shift compensation, the resulting baseband signal is $z(t) = \tilde{z}(t)e^{-j2\pi f_c t}e^{-j2\pi \epsilon t}$, where $\epsilon$ is the estimated carrier frequency offset (CFO) as described in [3]. The FFT output $z_m$ at the $m$th subcarrier, where $m = -K/2, ..., K/2 - 1$, is

$$z_m = \int_{0}^{T'} z(t)e^{-j2\pi \frac{m}{T'} t} dt. \quad (8)$$
The receivers to be described will be based on different assumptions on the relationship between the baseband input signal $x(t)$ and the baseband output signal $z(t)$. In particular, we can write

$$z(t) = x(t) * h(t, \tau) + n(t),$$

(9)

where $*$ denotes convolution, $h(t, \tau)$ is the equivalent baseband channel, and $n(t)$ is the additive noise.

A. ICI-Ignorant Receivers

The ICI-ignorant receivers view the equivalent channel $h(t, \tau)$ to be time-invariant. As such, we obtain

$$z_k = H_k s_k + v_k,$$

(10)

where $H_k$ is the frequency response on the $k$th subcarrier of the channel $h(\tau)$,

$$H_k = \int h(\tau) e^{-j2\pi k \tau T} d\tau,$$

(11)

and $v_k$ is additive noise. ICI-ignorant algorithms use the measurements on the pilot subcarriers $z_{\{i_m\}}$ to estimate the channel $h(\tau)$. Once the channel estimate is available, one-tap data demodulation is done per subcarrier.

There are various channel estimation methods available. In this paper, we will study the following two:\footnote{Another available algorithm is orthogonal matching pursuit (OMP); the channel model used is the same as in the BP case, only an OMP receiver iteratively reconstructs the channel paths. OMP has been used to estimate sparse UWA channels in [11] for single carrier and in [12] for multicarrier systems. In our previous work we found that the BP algorithm consistently outperformed the OMP algorithm [8]; we therefore limit this study to BP only.}

- **LS channel estimator:** The channel is assumed to have $L$ taps when sampled at the symbol rate. In particular, we have

$$h(\tau) = \sum_{l=0}^{L-1} h_l \delta(\tau - lT/K),$$

(12)

$$H_k = \sum_{l=0}^{L-1} h_l e^{-j2\pi kl/K}.$$  

(13)
The LS channel estimator can be efficiently implemented through two FFTs, as described in [3].

- **BP estimator:** The receiver assumes a baseband channel with \( N_p \) paths where the path delays are in continuous time, such that

\[
h(\tau) = \sum_{p=1}^{N_p} \zeta_p \delta(\tau - \tau_p)
\]  

(14)

\[
H_k = \sum_{p=1}^{N_p} \zeta_p e^{-j2\pi k \frac{\tau_p}{T}}
\]  

(15)

The channel support \( \tau_{N_p} - \tau_1 \) could be large, however, the channel is assumed to be sparse, where \( N_p \) is much smaller than the number of pilot subcarriers. Sparse channel estimation is accomplished via convex optimization, where fitting the channel measurements is balanced by the minimization of the \( l_1 \) norm of the channel amplitudes. In this paper, we adopt the implementation in [13].

**B. Basis Expansion Model Based Receivers**

In the BEM based receivers, the time varying channel is decomposed into three time invariant channels along three bases as:

\[
h(t, \tau) = h^+(\tau)e^{j2\pi t/T} + h(\tau) + h^-(-\tau)e^{-j2\pi t/T}.
\]  

(16)

The channel output at the \( k \)th subcarrier will accordingly have contributions from three symbols as

\[
z_k = H^+_{k-1}s_{k-1} + H_k s_k + H^-_{k+1}s_{k+1} + v_k.
\]  

(17)

One key assumption in the BEM receiver is that the three channels \( h^+(\tau) \), \( h(\tau) \), and \( h^-(-\tau) \) are independent, and shall be estimated separately.

Two receivers can then be constructed for this model:

- **Parallel LS channel estimators.** One LS channel estimator uses the measurements on the pilot subcarriers to estimate \( h(\tau) \), one estimator uses the measurements on \( \{i^+_m\} \) to estimate \( h^+(\tau) \), while another one uses the measurements on \( \{i^-_m\} \) to estimate \( h^-(-\tau) \).

- **Parallel BP channel estimators.** Similar to LS, three BP channel estimators are adopted. Once channel estimates are available, a zero forcing receiver is used to mitigate the ICI among data symbols [1].
C. Receiver with a Path-Based Model

As in [1], [8], the passband channel between $\tilde{z}(t)$ and $\tilde{x}(t)$ [c.f. Fig. 2] is assumed to have $N_p$ discrete paths, and each path is parameterized by a triplet $(A_p, b_p, \tau_p)$, where $A_p$ is the amplitude, $b_p$ is the Doppler scaling factor, and $\tau_p$ is the delay. (17) can still be applied here, however, $H_{k^+}^i$, $H_k$, and $H_{k^-}^i$ are now related to each other via the path-based channel model. Through the derivations in [1], [8], we obtain:

\begin{align}
H_k &= \sum_p A_p e^{-j2\pi(f_k + \epsilon)\tau_p} \left[ \text{sinc} \left( \pi \beta_k T \right) e^{j\pi \beta_k T} \right], \\
H_{k^\pm}^i &= \sum_p A_p e^{-j2\pi(f_k \pm \frac{1}{T} + \epsilon)\tau_p} \left[ \text{sinc} \left( \pi \beta_{k^\pm} T \right) e^{j\pi \beta_{k^\pm} T} \right]
\end{align}

where $\text{sinc}(x) = \sin(x)/x$ and

\begin{align}
\beta_k &= \frac{b_p f_k - \epsilon}{1 + b_p}, \\
\beta_{k^\pm} &= \pm \frac{1}{T} + \frac{b_p f_k - \epsilon}{1 + b_p}.
\end{align}

Based on all the observations of the set $\{i_m^-, i_m, i_m^+\}$, one can use BP (or OMP) to estimate those $N_p$ distinct paths along a two-dimensional grid of possible delay and Doppler scale values. Once channel estimates are available, a zero forcing receiver is used to mitigate the ICI among data symbols [1].

IV. Experimental Results: GLINT’08

Data from the GLINT experiment was collected from a drifting transmitter ship (moving at a speed from anywhere between 0.5 and 2 knots) positioned on an average distance of 1 km from the receiver, in the area around Pianosa, just south of Elba, off the coast of Italy. The water depth is about 100 m. We focus on the data collected on three days, the 25th, 26th, and 27th of July 2008, each of which contains five transmissions of 45 OFDM blocks per transmission (15 containing QPSK, 15 containing 16-QAM, and 15 containing 64-QAM).

The center frequency was $f_c = 25$ kHz and the bandwidth was $B = 7.8125$ kHz. The sampling rate was $f_s = 250$ kHz. The number of subcarriers is $K = 1024$, which leads to subcarrier spacing of $B/K = 7.6294$ Hz and symbol duration of $T = 131.1$ ms. The guard time was set as $T_g = 25$ ms. A rate-1/2 nonbinary LDPC channel code [14] was used to map 336 information symbols to 672 coded symbols. The achieved data rates after accounting for all overheads are 2.15 kb/s, 4.30 kb/s, and 6.45 kb/s, for QPSK, 16-QAM, and 64-QAM, respectively.
Fig. 3. Comparison between BEM and path-based channel model using an example channel recorded at the GLINT’08 experiment; we note that the Doppler spread is small (BEM time-varying channels are magnified ×4), and that there is obvious correlation in BEM, see, e.g., last peak.

A. Channel Conditions

We first focus on a single channel estimate for illustrative purposes, see Fig. 3. On the left, Fig. 3(a), we see the time domain estimates along the three bases. Since they are estimated independently, the center estimate is equivalent to the ICI-ignorant channel estimate. Inspecting the ICI-ignorant channel estimate, we first notice that the channel is sparse: a delay spread of more than 10 ms, but at most five significant paths\(^2\). Comparing to the time-varying components of the BEM, we notice two things: i) the power on the time-varying components is relatively small (the plots are magnified); and ii) the arrivals happen at the same delays, especially at the late arrivals. This makes the assumption of independent bases seem sub-optimal.

The path-based estimate is shown in Fig. 3(b), where the color-surface is a correlation of possible delay/Doppler values with the observations on the pilots. The sparse estimator will only choose a subset, indicated by the markers. The x-axis is labeled Doppler speed, the time-

\(^2\)It is also interesting to notice that there is a weak early arrival at 4 ms, our interpretation is that this is in fact the direct path, but the main power of the transmit array is steered towards the bottom, making the bottom-reflected paths stronger.
variation in path-length. We see that most paths have a Doppler speed less than 0.05 m/s, where the arrivals around $\tau = 14$ ms have the most significant spread. The link between the two models is that a path of a certain delay, with a non-zero Doppler speed, will lead to peaks at the same delay showing in the time-varying bases, whereby the amplitude depends on the Doppler speed.

![Energy ratio](image.png)

**Fig. 4.** The ratio of the energy measured on the pilot subcarriers to that measured at the neighboring null subcarriers; GLINT’08 data.

For every OFDM block we measure the severity of residual ICI induced by Doppler spread through computing the ratio between the energy at the pilot-containing subcarriers to the energy at the “left and right” neighbors to those subcarriers, i.e.,

$$\text{Energy ratio} = \frac{\sum_{m=1}^{M} |z_{i_m}|^2}{\sum_{m=1}^{M} |z_{i_m} - m|^2 + |z_{i_m} + m|^2}.$$  \hspace{1cm} (21)

In Fig. 4 we observe that the energy ratio is found to be mostly around 15 dB. This shows that the residual ICI can be ignored and that ICI-ignorant receivers should perform well. On the other hand we still expect to gain by using sparse channel estimation.

**B. Performance Results**

To analyze performance results we chose a block-error-rate (BLER) criterion, which is defined as the average number of OFDM blocks that cannot be recovered error-free after LDPC decoding. We plot this metric using an increasing number of receiver phones, where maximum ratio combining (MRC) is used to increase effective SNR.
We first inspect the QPSK performance across all days, see Fig. 5, where we notice no significant differences between the five receivers. Although all QPSK data can be decoded without errors, at an approximate SNR of more than 10 dB we would expect better performance. Only on July 27 the performance is as expected, and we are also able to decode higher constellation data, see Fig. 6. Especially in the higher constellation data, we can see significant advantages of the sparse channel estimators, where the path-based model and the ICI-ignorant BP are slightly better than the BEM based BP receiver. The ICI-ignorant LS receiver from [3] is always superior to the LS receiver with BEM.

![Fig. 5. Performance results for GLINT’08 experiment; the performance differences are generally limited for QPSK data; path-based receiver uses BP.](image)

V. EXPERIMENTAL RESULTS: SPACE’08

Experimental data is collected from the SPACE 2008 experiment, which was held off the coast of Martha’s Vineyard, Massachusetts, U.S., during October 2008. The water depth was about 15 meters. The transmitter was about 4 meters above the sea floor, while the receiver arrays were about 3.25 meters above the sea floor. Six receivers were in place, labelled as S1 (60 m, Southeast), S2 (60 m, Southwest), S3 (200 m, Southeast), S4 (200 m, Southwest), S5 (1000 m, Southeast), and S6 (1000 m, Southwest). In this paper, we analyze experimental data collected on the Julian dates from 295 to 300 (Oct. 21 – 26), at the Southesast receivers.

The system bandwidth was $B = 9765.625$ Hz with a center frequency of $f_c = 13000$ Hz. We used $K = 1024$ subcarriers giving a subcarrier spacing of $B/K = 9.5367$ Hz. Out of
Fig. 6. On July 27 the channel conditions allow for transmission of high constellation data; here the difference are more visible, where the path-based receiver is the best and the BEM receivers are sometimes equal and sometimes worse than the ICI-ignorant receivers.

Fig. 7. Above: average wave height for selected days of SPACE 2008 experiment. Below: average wind speed for the same range of days.

1024 subcarriers, there are $N_d = 336$ data subcarriers and $N_p = 128$ pilot subcarriers. With a constellation of size $M$ and rate 1/2 nonbinary LDPC coding [14], the spectrum efficiency is

$$\alpha = \frac{T}{T + T_g} \cdot \frac{336}{1024} \cdot \frac{1}{2} \cdot \log_2 M. \tag{22}$$

For QPSK, 16QAM, and 64QAM, the spectrum efficiencies are 0.2658, 0.5315, and 0.7973 bits/s/Hz, respectively, while the achieved data rates are 2.60, 5.19, and 7.79 kb/s, respectively.
A. Channel Conditions

Since the experiment was conducted in the open ocean, as opposed to a bay or harbor environment, we expect the sea state to be more dramatic. In Fig. 7, the average wave height and speed is plotted for part of the experiment. We notice that there is a significant peak in the morning of Julian date 300.

An example channel time-domain estimate is plotted in Fig. 8, which was recorded on the morning of Julian date 300 at receiver S1. We notice that the arrivals are not as “crisp” as in the GLINT’08 data, and that there is significantly more Doppler activity. Also the delay spread is shorter, no more than 8 ms in this example. Otherwise the same links between the models can be made. To further substantiate our claim of more dramatic conditions, we plot the energy ratio for Julian date 300 in Fig. 9. We see that it is largely below 10 dB with some significant fades in between.

B. Performance Results

As before we focus on BLER as performance metric. In this experiment each receiver has a large number of phones that we can use to illustrate performance; we use up to twelve phones
for the MRC. In Table I, we include performance results for QPSK, 16-QAM, and 64-QAM, in combination with receivers S1, S3, and S5. The performance is averaged across Julian dates 295 – 300.

1) QPSK: As in the GLINT experiment, the QPSK data shows no big performance differences between the various receivers. All blocks could be decoded without error combining two to five phones.

2) 16-QAM: At the higher constellation data we notice more differences between the various receiver algorithms, but also between receiver locations. Typically S1 is challenging in terms of delay and Doppler spread due to the short distance, while S5 naturally has the lowest SNR due to the distance.

Comparing the receiver algorithms, the path-based receiver has always the best performance, followed by either the ICI-ignorant or the BEM sparse estimator (all using BP). The two least-squares estimators are always the worst, with usually the BEM receiver trailing the ICI-ignorant.

We now plot separately two individual days, Julian dates 299 and 300, to point out deviations from the average behavior, see Table II. Although Julian date 299 has much more benign weather than Julian date 300, they are both examples for the Doppler rich geometry at receiver S1. At the short distance the ICI is by far the limiting factor, and both the path-based and the BEM receivers clearly outperform the ICI-ignorant receivers. At a longer distance, i.e., S5, the ICI-
TABLE I
PERFORMANCE RESULTS FOR SPACE’08 EXPERIMENT, AVERAGED ACROSS JULIAN DATES 295-300.

<table>
<thead>
<tr>
<th></th>
<th>S1 (60 m)</th>
<th>S3 (200 m)</th>
<th>S5 (1,000 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK across days</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
</tr>
<tr>
<td>16-QAM across days</td>
<td><img src="image4" alt="Graph" /></td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td>64-QAM across days</td>
<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
<td><img src="image9" alt="Graph" /></td>
</tr>
</tbody>
</table>

ignorant receivers outperform the the BEM receivers.

3) 64-QAM: Using the highest constellation in our experiment, the 64-QAM performance increasingly depends on the available SNR that is limited not only by ICI, but also by transmission distance. In Table I, we see that the path-based receiver can decode all OFDM blocks at receivers S1 and S3. Otherwise the order is similar to the case of 16-QAM.
TABLE II
Performance results for SPACE’08 experiment, 16-QAM, on two specific days.

<table>
<thead>
<tr>
<th>16-QAM</th>
<th>S1 (60 m)</th>
<th>S3 (200 m)</th>
<th>S5 (1,000 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Julian date 299</td>
<td>10^3</td>
<td>10^2</td>
<td>10^1</td>
</tr>
<tr>
<td>Julian date 300</td>
<td>10^0</td>
<td>10^1</td>
<td>10^2</td>
</tr>
</tbody>
</table>

VI. CONCLUDING REMARKS

In this paper, we compared various receivers for an OFDM signal design assuming that the residual intercarrier interference is limited only to direct neighboring subcarriers. Based on performance results from the GLINT’08 and SPACE’08 experiments, we have the following observations.

- For channels with low Doppler spread or systems with a small size constellation, all receivers
work well. When the channel’s Doppler spread or the signal constellation size increases, the performance differences among different receivers drastically increase.

- BEM based receivers are often inferior to the ICI-ignorant counterparts, unless the channel has a very large Doppler spread, the benefit of ICI compensation may be offset by the estimation errors on the much increased number of BEM parameters.

- The receiver based on the path-based model and the BP algorithm achieves the best performance. Associating different paths with different Doppler scales, the ICI pattern can be captured without increasing the number of unknowns. This receiver offers a much enhanced capability to handle channels with large Doppler spread.

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