Multicarrier Communication for Underwater Acoustic Channels with Large Doppler Spread

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Our goal: fast underwater acoustic (UWA) single-user communications

- High SNR operation
- Faster communication requires minimizing self-interference

OFDM with no channel effects before sampling (top) and after sampling (bottom)
Time Domain Interference is not an Issue

- Paths arrive at different times, causing time-domain spreading
- Arrivals are sparse in nature
- Zero padding avoids intersymbol interference
Frequency Domain Interference Is

- Paths are associated with different Doppler scales
- Symbols overlap in frequency domain

Vertical axis: time, horizontal axis: frequency

Presenter: Sean Mason
Why Doppler Spreading Happens

- **Channel model:** \( c(t, \tau) = \sum_p A_p \delta(\tau - (\tau_p - a_p t)) \)
  - Multiple arrival paths with unique Doppler scales, \( a_p \), and gains, \( A_p \).
  - Time varying multipath structure
  - Differing Doppler scales result from irregular surface motion
The Result of Doppler Spreading

- Subcarrier 1’s sample includes information from subcarrier 2 (and vise versa)
- Performance is limited even without external noise

OFDM in 3 tap Doppler channel before sampling (top) and after sampling (bottom)
Nulls separate pilots from data

A Doppler spread of about 2 can be tolerated
At the receiver, we have measurements $y_k(m)$, at group $m$, subcarrier $k$.

- $m = \{0, \ldots, K/8\}$, $k=\{0,\ldots,7\}$
- Doppler spread is quantified as:
  
  Energy ratio (left) = \[ \frac{\sum_m |y_1(m)|^2}{\sum_m |y_0(m)|^2} ; \]
  
  Energy ratio (right) = \[ \frac{\sum_m |y_1(m)|^2}{\sum_m |y_2(m)|^2} ; \]
We define three choices for Doppler Despreading/ICI consideration

- **ICI ignorant channel estimation**
  - Only use pilot information from subcarrier 1
  - Generate a one-dimensional channel estimate
  - Only use data measurements from subcarriers 4-6

- **ICI independent channel estimation**
  - Use pilot information from subcarriers 0-2
  - Combine three one-dimensional channel estimates (using $y_0$, $y_1$, and $y_2$ independently)
  - Use data measurements from subcarriers 3-7
  - This is FFT basis expansion

- **ICI joint channel estimation**
  - Use pilot information from subcarriers 0-2
  - Generate one two-dimensional channel estimate
  - Use data measurements from subcarriers 3-7
ICI Considerations

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Compressed Sensing (1)

- The UWA channel is highly spread, but sparse
- Least squares (LS) channel estimation: $\hat{h} = \min_{h} |y - sh|^2$:
  - Does not take advantage of sparseness
  - Cannot estimate a channel with delay longer than the number of pilots
- Compressed sensing (CS):
  - Will improve performance for ICI ignorant and ICI independent receivers
  - Allows for two dimensional (ICI joint) channel estimation
Represent the channel using an overcomplete dictionary
Each element corresponds to a delay, $\tau_p$, and a Doppler scale, $a_p$
For example, $\text{element}(\tau_p, a_p) = A_p \delta(t - \tau_p)e^{j2\pi a_p t}$
Orthogonal Matching Pursuit (OMP)
- Iteratively defines values from the dictionary
- Solves a LS problem at each iteration
- Stopping criterion based on noise estimate

Basis Pursuit (BP)
- Chooses a dictionary representation with minimal $l_1$ norm
- Determines $\min_{h} |y - sh|^2 + \lambda|h|_1$
- More robust than OMP, and better as the channel becomes non-sparse
- Also iterative: stopping criterion based on desired fitting error
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Eight receivers are used on experimental data.

Each is characterized by channel estimation method and ICI considerations adopted.

<table>
<thead>
<tr>
<th>ICI Consideration</th>
<th>LS</th>
<th>OMP</th>
<th>BP</th>
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</thead>
<tbody>
<tr>
<td>Ignorant</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Independent</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Joint</td>
<td>N/A</td>
<td></td>
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SPACE 2008, off the coast of Martha’s Vineyard, MA

- Examine QPSK, 16-QAM, and 64-QAM data
- Single transmitter with up to 12 receivers
- 1024 total subcarriers per block, with 128 pilot, 336 data

Wave height by day, before, during, and after transmission, for SPACE 2008 experiment

Energy ratios by day for SPACE 2008

Presenter: Sean Mason
Coded BER results, Day 298 (October 24)

- Coded BER results for day 298
- Left: 16-QAM, right: 64-QAM
- Calm sea state with little Doppler spreading
Coded BER results, Day 300 (October 26)

- Coded BER results for day 300 (coded BER vs phones used)
- Upper left: QPSK, left: 16-QAM, above: 64-QAM
- Joint BP receiver is the best choice on the worst day
Coded BER results, Day 302 (October 28)

- Coded BER results for day 302
  (coded BER vs phones used)
- Upper left: QPSK, left: 16-QAM, above: 64-QAM
- Joint BP receiver is best (no clear choice again for QPSK)
ICI independent vs joint estimation
   - ICI joint receivers beat ICI independent receivers in theory and practice
   - ICI independent receivers poorly represent a 2 dimensional channel

LS estimation
   - LS rarely beats OMP or BP
   - Independent LS is usually worst

BP estimation
   - Shown to be a better choice than OMP
   - Joint BP almost always has best performance, even with calm sea
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Conclusions

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