Recent Advances in Coherent Communication over the underwater acoustic channel

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Outline

- Motivation & Applications
- UWA Channel modeling
- Single Carrier Freq Domain Equalization SC-FDE
- Coded Modulation for the UWA channel

- Collaborators over the years: Darrell Jackson, Warren Fox, Dan Rouseff (UW-APL)
- Q Wen, B Song, J Flynn, C Polprasert (UW EE students)
Applications

- Military Sensing and C^3I
- Homeland Security
- Environmental Sensing
- Undersea drilling & mining
- Interesting research arena
  - Dispersive channel that is time varying, and stochastic
  - Rich physical modeling
  - Resurgent applications
  - Experimental program
Understanding the UWA Channel

- Channel is a time-varying linear filter
- Many channels from each transmitters to each receiver
- Channel characterized by its delay spread and coherence time
- Some data from our Puget Sound experiment in 2000
Telemetry Configuration

- Transmitter: $F_c = 12$ kHz
- Receiver Sensor Array
  - 1
  - 2
  - 3
- Distances:
  - 15 m
  - 38 to 84 m
  - 28 m
- Range: 0.9 to 4.6 km
Telemetry: FIR (MA) Channel characterization

Transmit "single pulse" 0.9 to 4.6 km

Transmitter $F_c = 12$ kHz

Receiver Sensor Array

1
2
3
Q

15 m
28 m
38 to 84 m

2 m
Array
Impulse
Response
in Shallow
Water

“Underwater Acoustic
Communication by Passive
Phase Conjugation:
Theory and Experimental
Results,” Rouseff, Jackson,
Fox, Jones, Ritcey,
Dowling, IEEE J. Oceanic

Transmit
single pulse

Multipath reflections
Array Impulse Response in Shallow Water

Look at time variation
Channel Impulse Response Evolution

- **Direct Paths** (no bounces)
- **Multiple bounces**
Large Delay Spread → Large ISI
Multi-channel Equalization

Channel

Channel EQ Filter Outputs

Joint Channel EQ Output

Need to compute EQ filters

TX Data Source

\( X_t \)

\( h^{(1)} \)

\( h^{(2)} \)

\( h^{(14)} \)

\( EQ^{(1)} \)

\( EQ^{(2)} \)

\( EQ^{(14)} \)

Symbol Estimate

\( \{+1,-1\} \)

Quant.
Block-Adaptive MC EQ Architecture
Evaluation, Data Set $\mathcal{A}$: 0.9 km
BER, trial $A$ (Gaussian approx.)
Block Based Transmission Systems

- Reduces Complexity
- Includes OFDM-CP OFDM-ZP & SC-DFE
- Intersperse Pilots (for channel estimation) and Data
- Outer code across multiple blocks
- Requires slower channel time variation
Block-Based Transmission

Fig. 2. Frame structure.

Pilot block

Data block
Orthogonal Frequency-Division Multiplexing (OFDM)

- Included in DAB/DVB standard in Europe and the DSL modem in the US
- Used in fixed broadband wireless systems
- Combats multi-path fading by transmitting orthogonal symbols in parallel using narrow-band sub-channels
- Two variants are considered based on the sequence inserted at the transmitter to avoid Inter-block Interference (IBI):
  - CP-OFDM
  - ZP-OFDM
CP OFDM Transmission block diagram

Input Stream $\{d_x\}$

- Transmitter -

Modulator $\{s_{x,n}\}$

S/P

IFFT

CP Insert

P/S $\{s_{x}'\}$

Fading channel $\{h_{x}\}$

AWGN noise $n$

- Receiver -

Demodulator $\{a_{x}\}$

P/S

Equalizer

FFT

CP Remove

S/P

Output Stream $\{y_{k,n}\}$
System Parameters - BPSK

- $R$  Bit rate (bits/s)
- $N$  No. of subcarriers, blocksize
- $P$  No. of CP or ZP samples
- $T = (N+P)/R$  OFDM Symbol duration (s)
- $\Delta f = R/N$  Subcarrier spacing (Hz)
- $B = N\Delta f$  Total Bandwidth (Hz)
Single-Carrier Frequency Domain Equalization (SC-FDE)

- Single Carrier alternative to OFDM\textsuperscript{1,2}
- Similar performance to OFDM with same computational complexity
- 2 variants
  - ZP-SC-FDE
  - CP-SC-FDE
- Frequency Domain Equalizer
  - Linear: Zero-forcing (ZF), Minimum Mean Square Error (MMSE)
  - Non-Linear: Decision feedback (DFE)
    - Frequency domain feedforward filter
    - Frequency or Time domain feedback filter\textsuperscript{2,3}

1-IEEE Std 802.16TM-2004
2-Falconer et al., 2002
3-Falconer 2002
CP SC-FDE
# OFDM & SC-FDE Comparison

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OFDM</strong></td>
<td>▪ Combats ISI using parallel narrowband transmission.</td>
<td>▪ Flat fading: channel coding is required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ High PAPR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>▪ Susceptible to frequency offset (ICI)</td>
</tr>
<tr>
<td><strong>SC-FDE</strong></td>
<td>▪ Yields multi-path diversity gain for uncoded transmission ▪ Low PAPR ▪ Resistance to frequency offset</td>
<td>▪ High computational complexity when calculating DFE coefficients</td>
</tr>
</tbody>
</table>

• PAPR: Peak-to-average power ratio
OFDM & SC-FDE

- **OFDM**

- **SC-FDE**

  - Increased computational complexity at the receiver
Iterative uncoded SC-FDE

- Demodulated data is fed back through the feedback filter
- Equalizer coefficients are updated by decision direction according to the data from the previous iteration
- Frequency domain feed-forward filter
- **Frequency domain feedback filter**\(^{1,2}\)
- Comparable performance to that of time-domain at lower computational complexity
- Iterative uncoded SC-FDE yields comparable performance to time-domain equalization with lower complexity due to FFT usage
- Pilots are used to estimate the channel
- A Chu sequence is periodically inserted to satisfy 2-dimensional sampling theorem
- Channel estimation using 2-Dimensional Wiener filtering
- Frame-based channel estimation

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Iterative SC-FDE with PSAM

Channel estimation
Channel estimation in SC-FDE

• Equalizer training using a known sequence with constant magnitude across the spectrum (Chu sequence\(^1\))
• Block-by-block channel estimation and tracking using LMS or RLS\(^2,3\)
• Iterative channel estimation and equalization within one FFT block\(^4\)
• In-band frequency domain multiplexed pilots\(^5\)
  ➢ Similar to OFDM at higher complexity
• Commonly used in wireless OFDM

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1-Chu, “Polyphase codes with good periodic correlation properties”, IEEE Trans Info 1972

LMS: Least Mean Square
RLS: Recursive Least Square
Chu-sequence

Constant magnitude across a transmission bandwidth
Pilot symbol assisted modulation (PSAM)

- Widely used in OFDM
- Pilot symbols are periodically inserted in both time and frequency with equal distance spacing
- Wiener filtering in both time and frequency domain

1-Sanzi et al., "A comparative study of iterative channel estimators for mobile OFDM", Sept 2003
Frame structure

1 Frame: \( N_t \) FFT Blocks

<table>
<thead>
<tr>
<th>Pilot Block</th>
<th>( N_t - 1 ) Data Block</th>
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\[ T_b \]

Fig. 2. Frame structure.

LP: Pilot block

Data block
Known symbols from pilot blocks are selected and filtered in both time and frequency domain to estimate channel fading.
UWA Channel fading simulator

- Time variation within each path is governed by Doppler spread
UWA channel at 700 meter depth

<table>
<thead>
<tr>
<th>Delay (ms)</th>
<th>0.0 2.25 2.75 4.375 5.125 11.875 12.875 16.125 17.25</th>
</tr>
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<tbody>
<tr>
<td>Power ($\times 10^{-4}$)</td>
<td>2.6 1.65 1.50 0.75 0.55 0.55 0.80 0.25 0.30</td>
</tr>
<tr>
<td>Doppler spread (Hz)</td>
<td>1.27 1.50 1.53 1.76 2.30 2.19 2.02 2.84 2.8</td>
</tr>
</tbody>
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Simulation parameters, $N_t = 1$

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<td>Mapping</td>
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<td>Number of FFT points ($N$)</td>
</tr>
<tr>
<td>Number of Frames Transmitted</td>
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<tr>
<td>Channel Equalization</td>
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<tr>
<td>Pilot Sequence</td>
</tr>
<tr>
<td>Pilot Spacing in time ($N_t$)</td>
</tr>
<tr>
<td>Number of pilots used for estimation in time ($2L_t$)</td>
</tr>
<tr>
<td>Number of pilots used for estimation in frequency ($2L_f$)</td>
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<tr>
<td>Symbol Duration (1/Bw)(ms)</td>
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<td>Bit rate (kbps)</td>
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Performance of the iterative SC-FDE with $N_t = 1$
Simulation parameters, $N_t = 2$

<table>
<thead>
<tr>
<th>Simulation parameters when $N_t = 2$</th>
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<tbody>
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<td>Transmission Frequency Band</td>
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<td>Symbol Duration (1/Bw)(ms)</td>
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<td>Bit rate (kbps)</td>
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Performance of the iterative SC-FDE with Nt = 2

EbNo(dB) vs. BER for different iterations and Perfect CSi.
Performance comparison between Nt=1 and Nt=2 at 4th iteration

Data rate and performance tradeoff
Turbo Equalization

- Huge improvement over conventional by exchanging information between the equalizer and the channel decoder
- Pioneered by Douillard\textsuperscript{1} using the MAP equalizer
  - excellent performance
  - high complexity for multi-level modulation
- Low complexity approaches:
  - Reduced states in the trellis structure\textsuperscript{2}
  - Linear equalizer: MMSE\textsuperscript{3,4}
  - Non-Linear equalizer: DFE\textsuperscript{5}
- Turbo equalization in frequency domain\textsuperscript{4} gives reasonable complexity/performance tradeoff for small-to-medium block length

\textsuperscript{1}Douillard et al., “Iterative correction of ISI: turbo equalization”, ETT, Sept 1995
\textsuperscript{2}Park and Gelfand, “Sparse MAP equalization for turbo equalization”, VTC’05 Spring.
BICM and BICM-ID Review

- Bit-interleaved coded modulation (BICM)
  - Large diversity order through bit-wise interleaving
  - First introduced by Zevahi, 1992
  - Thorough analysis
- BICM with iterative decoding (BICM-ID)
  - Constellation labeling design
  - 8-PSK: Li and Ritcey, 1997
  - 16-QAM: Chindapol and Ritcey, 1999
  - Imperfect CSI over Rayleigh fading: Huang and Ritcey 2003
  - Space Time Block Codes: Huang and Ritcey 2005
Frequency-domain Turbo Equalization with BICM-ID
Frequency domain linear MMSE equalizer

\[ \hat{x}_n \rightarrow \text{P/S} \rightarrow \text{IFFT} \rightarrow \hat{x}_{k,n} \rightarrow Y_{k,n} \rightarrow \text{FFT} \rightarrow \text{S/P} \rightarrow \{y_n\} \]

\[ \bar{x}_{k,n} \rightarrow \text{FFT} \rightarrow \text{S/P} \rightarrow \bar{x}_n \]

\[ C_{k,n} \rightarrow \text{Equalizer Coefficient} \rightarrow H_{k,n} \]

\[ \bar{x}_{k,n} \rightarrow B_{k,n} \]

Received symbol

Channel fading

Information from the previous iteration
ISI is suppressed when EbNo is equal to 3.1 dB
Application to UWA

- Coherent Signaling – Channel Estimation
- Iterative channel estimation decoding
- Integration with OFDM and SC-FDE
- Application to UWA realistic channels
Upcoming Work

• BICM/BICM-ID over OFDM/SC-FDE
  ➢ Perfect CSI
    • Use iterative decoding to combat multi-path fading
    • Impact of labeling, code rate over the BER performance
    • Its performance over different types of equalizer e.g. DFE, MMSE
    • Adaptive modulation and equalization
  ➢ Imperfect CSI
    • Use iterative decoding to combat imperfect estimate of the fading
  ➢ Array Combining
  ➢ Joint estimation and decoding