An Underwater Acoustic Telemetry Modem for Eco-Sensing*

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WetNet Implemented with AquaNodes

Applications: Santa Barbara Channel LTER, Moorea Coral Reef LTER and many more.
Modem Alternatives

• Commercial modems: (Benthos, Linkquest…)  
  – Too expensive, power hungry for Eco-Sensing. Proprietary algorithms, hardware.  
  – M-FSK (Scussel, Rice 97, Proakis 00) does use frequency diversity, but requires coding to erase/correct fades.

• Navy modems:  
  – Need open architecture for international LTER community – precludes military products.

• Direct-sequence, QPSK, QAM, coherent OFDM  
  – Great deal of work on DS, QPSK for underwater comms. But equalization, channel estimation are difficult. (Stojanovic 97, Freitag, Stojanovic 2001, 2003.)

• MicroModem:  
  – Best available solution for WetNet. FSK/Freq. Hopping relies on coding to correct bad hops.  
  – But can we do better? Less power? Wider bandwidth for lower uncoded symbol error rate (SER)?

• AquaNode modem: Uses Walsh/m-sequence signalling, matching pursuits channel estimation.  
  – Uses per-symbol frequency diversity.  
  – Motivated by 802.15.4 (Zigbee), 802.11b m-ary quasi-orthogonal waveforms.  
  – Achieves 133 bps data rate without need for equalization, accurate carrier phase tracking.  
  – Battery life in months for reasonable transmit duty cycles.  
  – Matching Pursuits only assumes channel constant over 22 msec.  
  – Far superior to FSK in slow fading (Doppler spread < .1 Hz) scenario using Kalman filter channel tracking.
Multipath/Doppler Spread References

- Long range shallow water multipath spread ~100 msec. (Kilfoyle and Baggeroer 00)
- 120 msec. spread at 48 nm, 5 msec. at 2nm shallow water (Stojanovic et. al. 94)
- Significant delay spread ~10 msec. 2-6 meter depth, 400-500m range. (Freitag et. al. JOE 01)
- 2.5 msec multipath spread, .5 Hz Doppler spread at 3km (6 to 30m depth) in Baltic. (Sozer et. al. 99)
- .67 msec. multipath spread for two-ray channel (Benson et. al. 00)
- Conjecture: A broad class of short range (< 500 m) shallow water channels exists with temporal multipath spread ~10 msec., Doppler spread < 1 Hz.
Walsh/m-sequence Signals

\[ d_m = b_m \otimes c \]

\[ (b_m)_1 = 1 \]
\[ (b_m)_2 = -1 \]
\[ (b_m)_8 = 1 \]

\[ T_{sym} = 11 \text{msec.} \]
\[ T_c = .2 \text{msec.} \]

\[ T_{sym} = 11 \text{msec.} \]
\[ T_g = 11 \text{msec.} \]
Motivation for Walsh/m-sequence Waveforms

- Wideband (5 kHz) yields frequency diversity.
- 3 bits/symbol yields $10 \log_3 = 4.8$ dB coding gain relative to binary FSK.
- Does not require accurate phase tracking for detection (c.f. QPSK, QAM.)
- Time-guard band eliminates need for equalization.
- Sparse channel estimation easily implemented via Matching Pursuits.
Wideband for Acoustic Comms -- Frequency Diversity Argument

- B Hz. Wideband signal can resolve multipaths $T_s = 1/2B$ apart.
- Classical RAKE receiver.

$$s(n) = 2E_s \sum_{k=1}^{L} |\alpha_k|^2 + \sum_{k=1}^{L} \alpha_k^* n_k$$
Channel, Walsh/m-sequence Spectra
Auto-Cross Correlation of Walsh/m-seq.
Un-coded SER Improvement with Diversity

FSK in Rayleigh Fading

\[ P_2 = \frac{1}{2 + \frac{E_b}{N_0}} \]

Binary Orthogonal with L-degree Diversity in i.i.d. Rayleigh Fading. Ideal RAKE – zero cross-correlation.

(J. G. Proakis 7.4.15)

\[ P_2 = \left( \frac{1 - \mu}{2} \right)^L \sum_{k=0}^{L-1} \binom{L-1}{k} \left( \frac{1 + \mu}{2} \right)^k \]

\[ \mu = \frac{E_b}{N_0 \left( \frac{E_b}{LN_0} \right) + 2} \]

Union Bound

\[ P_e < (N_w - 1)P_2 \]

Law of Large Numbers Interpretation – Normalized Channel Energy

\[ E\{|\alpha_k|^2\} = \frac{1}{L} \]

\[ 2E_s \sum_{k=1}^{L} |\alpha_k|^2 \to 2E_s LE\{|\alpha_k|^2\} = 2E_s \]
Union Bound SER -- Frequency Diversity

![Graph showing Union Bound SER for various diversity orders and modulation schemes.](image-url)
Received Signal Model

Transmitted Walsh/m-sequence

\[ s_m(n)(t) = \sum_{i=0}^{N_w L_p n - 1} (d_{m(n)})_i g(t - iT_c) \]

Received signal

\[ r(t) = \sum_{p=1}^{N_\alpha} \alpha_p(n) s_m(n)(t - \tau_p(n)) + n(t) \]

Nyquist-sampled equivalent vector signal

\[ \mathbf{r}(n) \approx \sum_{l=0}^{N_s - 1} f_l s_{m(n)}(l) + \mathbf{n}(n) = \mathbf{S}_{m(n)} \mathbf{f} + \mathbf{n}(n) \]
Matching Pursuits Channel Estimation

- Conventional LS estimate is “noisy” for sparse channels ($N_f << \text{components of } \mathbf{f} \text{ are nonzero.}$)
- Assume “minimum underspread” channel. Coefficients $\mathbf{f}$ are constant only during one symbol+time guard interval (22.4 msec.)
- Matching Pursuits (Mallat and Zhang, Cotter and Rao 02, Kim and Iltis 04) yields sparse channel estimates and is readily implemented in reconfigurable hardware (Meng et. al. DAC 05.)
MP Algorithm

• Step 1 – Conventional LS, best fit.

\[ \hat{f}_i = s(i)^H r / ||s(i)||^2, i = 1, \ldots, N_s \]

\[ q_1 = \arg \min_i \left| \left| r - s(i)\hat{f}_i \right| \right|^2 \]

\[ = \arg \max_i |\hat{f}_i|^2 ||s(i)||^2 \]

Step k – Cancel previous k-1 detected paths, find q_k

\[ r^k = r - \sum_{i=1}^{k-1} s(q_i)\hat{f}_{q_i} \]

\[ \hat{f}_i = s(i)^H r^k / ||s(i)||^2 \]

\[ q_k = \arg \min_{i \neq q_1, \ldots, q_{k-1}} \left| \left| r^k - s(i)\hat{f}_i \right| \right|^2 \]

\[ = \arg \max_{i \neq q_1, \ldots, q_{k-1}} |\hat{f}_i|^2 ||s(i)||^2 \]
GMHT-MP Algorithm

- Decision on $m(n)$ using Generalized Multiple Hypothesis Test (GMHT)

$$\hat{m} = \arg \min_m \left\{ \min_{f: \eta(f) = N_f} \| r(n) - S_m f \|^2 \right\}$$

GMHT has complexity $N_w \text{ binom}(N_s, N_f)$ due to numerosity constraint. For $N_f = 12$ paths, this requires $35 \times 10^{15}$ LS channel estimates requiring matrix-vector multiplies!

MP estimation requires $N_w N_s!/(N_s-N_f)! = 1.7 \times 10^{25}$ least-squares estimates, but these are scalar quantities. MP also only requires one matrix-vector multiply when implemented using sufficient statistics. GMHT-MP thus has the form

$$\hat{m} = \arg \min_m \left\{ \| r(n) - S_m \hat{f}^{MP,m} \|^2 \right\}$$
Sufficient Statistics MP Implementation
(A. Brown and Y. Meng, DAC 05)

• Step 1: Matrix-vector multiply
\[ v^1 = S^H r(n), \quad A = S^H S \quad \text{(look-up table)} \]
\[ q_1 = \arg \max_i \frac{|v^1_i|^2}{A_{i,i}}, \]
\[ \hat{f}_{q_1} = \frac{v^1_i}{A_{i,i}} \]
\[ v^2 = v^1 - A(:, q_1) \hat{f}_{q_1} \]

Step k: Does not require further matrix-vector multiplies.
\[ q_k = \arg \max_i \frac{|v^k_i|^2}{A_{i,i}}, \]
\[ \hat{f}_{q_k} = \frac{v^k_i}{A_{i,i}} \]
\[ v^{k+1} = v^k - A(:, q_k) \hat{f}_{q_k} \]
Reconfigurable Hardware MP-Core (Kastner, Meng, Brown)

Input \((r, S, A, a)\)

Output \((f)\)

// \(r\): received signal vector
// \(S\): \(S=[S_1, \ldots, S_N]\)
// \(A\): \(A=[A_1, \ldots, A_N]\)
// \(a\): \(a=[a_1, \ldots, a_N]\)^T
// \(f\): estimated channel coefficients

\[
\text{MP}(r, S, A, a) \\
	ext{for } i = 1, 2, \ldots, N \\
\begin{align*}
&V_i^0 \leftarrow S_i^T r \\
&f_i \leftarrow 0 \\
&g_k \leftarrow 0 \\
&\text{end for}
\end{align*}
\]

// do successive interference cancellation
\[
\text{for } j = 1, 2, \ldots, N_f \\
\begin{align*}
&V^j \leftarrow V^{j-1} - f_{q_j} A_{q_j} \\
&\text{for } k = 0, 1, \ldots, N_k - 1 \\
&\quad g_k \leftarrow v_j a_k \\
&\quad Q_k \leftarrow (v_j^*) g_k \\
&\text{end for} \\
&q_j \leftarrow \arg\max_{k \in \{0, 1, \ldots, q_j\}} |Q_k| \\
&f_{q_j} \leftarrow g_{q_j} \\
&\text{end for}
\end{align*}
\]

return \((f)\)

(a) Matched filter  
(b) Multipath successive interference cancellation  
(c) Matching pursuit algorithm for channel estimation
\[
\begin{bmatrix}
    r(0) \\
    r(1) \\
    \vdots \\
    r(223)
\end{bmatrix}
\]

Note: 112 Nyquist samples/symbol + 112 samples for channel clearing.
Matching Pursuits Channel Estimation

\[ N_\alpha = 12, \quad N_f = 16, \quad E_s/N_0 = 20 \text{ dB} \]
Matching Pursuits SER – Fixed Order

$\frac{E_s}{N_0}$ vs. SER for different modulation schemes:
- AquaNode/GMHT-MP $N_\alpha = 12$ $N_f = 16$
- RAKE $N_\alpha = 12$ $N_f = 16$
- FSK/SFH $N_\alpha = 12$ $N_f = 16$
Channel Order Estimation

• MDL and AIC yield overparameterized channel estimates.
• Modified MDL uses penalty term increasing with SNR and channel order, but requires optimization of penalty weight.
• Heuristic algorithm: Stop when decrease in error is below a threshold.

\[
\hat{N}_f = k \quad \text{if} \quad \left| \mathbf{r}(n) - \sum_{i=1}^{k} \mathbf{s}(q_i) \hat{f}_{q_i} \right|^2 > \beta \left| \mathbf{r}(n) - \sum_{i=1}^{k+1} \mathbf{s}(q_i) \hat{f}_{q_i} \right|^2
\]

Typical values of \( \beta \) are .95, .98.
SER Using Residual-Based Order Estimation

$E_s/N_0$ vs. SER for different modulation schemes:
- MP $N_\alpha = 12$, $N_f = 16$
- RAKE $N_\alpha = 12$, $N_f = 16$
- FSK/SFH $N_\alpha = 12$, $N_f = 16$

Using Residual-Based Order Estimation
$\varepsilon = .98$
Kalman Filter Channel Estimator

- MP only requires channel constant over $T_{sym} = 22.4$ msec. Good solution for large Doppler spreads (> .1 Hz.)
- For Doppler spreads $f_d < .1$ Hz, Kalman filter channel estimator is promising.
- Use decision-directed KF with process/measurement models

$$\hat{m}(n) = \arg \min_m \| \mathbf{r}(n) - S_{\hat{m}} \hat{f}(n|n-1) \|^2$$

$$\mathbf{f}(n+1) = \alpha_f \mathbf{f}(n) + \mathbf{w}(n)$$
$$\mathbf{r}(n) = S_{\hat{m}(n)} \mathbf{f}(n) + \mathbf{n}(n)$$
\[ P(n|n)^{-1} = P(n|n-1)^{-1} + \frac{1}{\sigma^2_n} S^H_{m(n)} S_{m(n)} \]

\[ \hat{f}(n|n) = \hat{f}(n|n-1) + P(n|n)S^H_{m(n)} \frac{1}{\sigma^2_n} [r(n) - S_{m(n)} \hat{f}(n|n-1)] \]

\[ \hat{f}(n+1|n) = \alpha_f \hat{f}(n|n) \]
Union Bound Conditional SER

- Analytic union bound SER speeds up KF simulations.
- Pairwise error probability.

\[
P_{1,2} = \frac{1}{2} \text{erfc} \left( \frac{\|S_1 f - S_2 \hat{f}\|}{\sigma_n} - \frac{\|S_2 (f - \hat{f})\|^2}{\sigma_n \|S_1 \hat{f} - S_2 \hat{f}\|} \right)
\]

SNR decrease due to estimation error

\[
P_e < \frac{1}{N_w} \sum_{i=1}^{N_w} \sum_{j=1}^{N_w} P_{i,j}
\]
Kalman Filter Channel Estimation

Multipath Intensity Profile

- True MIP
- Unconstrained Kalman Filter Estimated MIP

Time (sec.)

Multipath Intensity Profile

\( f_d = 0.05 \text{ Hz} \)

\( E_b/N_0 = 8 \text{ dB} \)
Example SER Trajectory – Doppler Spread = .05 Hz

Symbol Number

$Pe$ vs Symbol Number

- Blue: Walsh/m-seq. Kalman Filter
- Red: Walsh/m-seq. A-priori known channel
- Green: Noncoherent FSK

$f_d = .05$ Hz
$Eb/N_0 = 8$ dB
Simulation/Analysis using Union Bound

\[ f_d = 0.05 \text{ Hz} \]
\[ N_\alpha = 12 \]
### Signal and Data Parameters

- **Data rate:** 133 bps
- **Chip duration** $T_c = .2$ msec.
- **Symbol duration** $T_{sym} = 11.2$ msec.
- **Time guard interval** $T_c = 11.2$ msec.
- **M-sequence length** $L_{pn} = 7$ chips.
- **Walsh sequence length** $N_w = 8$
- **Bandwidth** = 5 kHz
- **Carrier Frequency** $f_c = 25$ kHz
- **Nominal range** 100 – 300 m.

### Power Consumption Overview

<table>
<thead>
<tr>
<th>Load</th>
<th>TX State</th>
<th>RX State</th>
<th>Sleep State</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td>440 mW</td>
<td>440 mW</td>
<td>.30 mW</td>
</tr>
<tr>
<td>CPU I/O</td>
<td>420 mW</td>
<td>420 mW</td>
<td>.15 mW</td>
</tr>
<tr>
<td>Flash Memory</td>
<td>165 mW</td>
<td>165 mW</td>
<td>.10 mW</td>
</tr>
<tr>
<td>Power Amp.</td>
<td>7.2 W</td>
<td>.05 mW</td>
<td>.05 mW</td>
</tr>
<tr>
<td>Battery Total</td>
<td>9.3 W</td>
<td>2.1 W</td>
<td>10 mW</td>
</tr>
</tbody>
</table>

### Battery Life (Based on 20 amp-hours)

<table>
<thead>
<tr>
<th>Tx Duty Cycle</th>
<th>Rx Duty Cycle</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>.1%</td>
<td>.2 %</td>
<td>624</td>
</tr>
<tr>
<td>.5%</td>
<td>1 %</td>
<td>189</td>
</tr>
<tr>
<td>1%</td>
<td>2%</td>
<td>101</td>
</tr>
</tbody>
</table>
Conclusions

• Walsh/m-sequence signaling exploits frequency diversity and yields lower uncoded SER than FSK.
• Matching Pursuits algorithm enforces sparse estimates, implemented in FPGA and DSP.
• Modem should be adaptive, using Kalman or MP channel estimation depending on sensed channel variation, velocity.
• Can a numerosity-constrained Kalman filter be developed? Better performance for $f_d > .1$ Hz?
• First generation modem implementable in DSP, but second gen. will require DSP +FPGA.