Acoustic Telemetry for UUVs using Walsh/m-sequence Waveforms *

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ABSTRACT

Underwater acoustic (UWA) telemetry requires wideband waveforms for anti-multipath which are simultaneously easy to equalize and demodulate. The Walsh/m-sequence waveforms proposed here are robust to multipath and with appropriate time-guard bands do not require equalization. For example, in the UCSB prototype acoustic modem, a data rate of 133 bps is achieved using 8-ary Walsh signaling with an 11.2 msec. symbol duration. Demodulation is performed using noncoherent detection, and hence accurate phase tracking, which is difficult to achieve in the UWA channel, is not required. However, telemetry from unmanned underwater vehicles (UUVs) is more problematic due to large Doppler shifts resulting from platform motion. A new receiver algorithm based on Matching Pursuits is proposed which combines channel and Doppler shift estimation. Symbol-error rate (SER) simulation results are presented for the UWA modem under realistic Doppler/multipath conditions.

KEYWORDS

Underwater acoustic telemetry, channel estimation, matching pursuits.

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INTRODUCTION

There is a great need for low-power, low cost and open architecture underwater acoustic telemetry modems for ecological research (eco-sensing) applications. In addition, gliders and UUVs are being increasingly deployed for eco-sensing [1][2], but acoustic modems for these applications are not widely available. Most underwater wireless networks developed so far for telemetry [3][4] rely on expensive, high power acoustic modems based on M-ary FSK [5][6]. In both stationary and mobile (UUV) UWA telemetry, the major obstacle to robust communications is multipath which introduces severe intersymbol interference (ISI). M-FSK modems use narrowband tones with duration much greater than the multipath spread, thus eliminating ISI. PSK modulation with equalizers [7] and direct-sequence spread-spectrum [8][9][10] modulation have also been implemented to reduce the effects of ISI and frequency-selective multipath.

UUV communications is further impaired by Doppler spreads and shifts due to platform motion. The ratio of platform motion to propagation velocity, v/c_s in the UWA channel is much larger than in terrestrial RF systems, since the sound speed underwater is $c_s \approx 1500$ m/s. Hence Doppler manifests as both a carrier frequency shift and signaling waveform compression. The WHOI acoustic Micromodem is one of the few Doppler-tolerant low-power designs that has been deployed in UUVs (Remus) [11][12]. However, the Micromodem relies on FSK/frequency-hopping to avoid frequency-selective multipath fading, and the level of Doppler tolerance and correction capability is not clear.

Acoustic UUV telemetry thus first requires a signaling waveform that is (a) instantaneously wideband for resistance to multipath, (b) easy to detect noncoherently so that phase tracking is not required, and (c) offers a sufficiently high data rate. Second, accurate channel estimation must be performed jointly with Doppler tracking and compensation, as the wideband signals will suffer from both carrier and "code" Doppler. The waveforms chosen here are based on composite Walsh/m-sequence (WMS) signaling, with a bandwidth of ≈ 5 kHz and target bit rate of 133 bps. The current UCSB modem specification based on WMS signaling can tolerate temporal multipath spreads of up to 11 ms. and Doppler spreads on the order of 1 kHz. Here, the problem of joint Doppler/channel estimation is solved using a modified Matching Pursuits (MP) algorithm [13][14] based on successive estimation and cancellation of multipaths. The overall receive modem is implemented using a Generalized Multipath Hypothesis Test (GMHT) combined with MP.

The following sections describe the UWA signal and channel models, GMHT-MP receiver, and conclude with representative channel/Doppler estimation simulations and SER results.

UWA SIGNAL, CHANNEL AND DOPPLER MODELS

The transmitted WMS signal is given by

$$s_T(t) = \sum_{n=0}^{\infty} (\mathbf{d}_{\mathsf{m}(n)})_i g(t - iT_c - 2nT_{sym}), \tag{1}$$

where $T_{sym} = 11.2$ ms. is the symbol duration and $T_c = .2$ ms. is the m-sequence chip duration. The pulse $g(t)$ is a raised-cosine with bandwidth β/T_c, $.5 < \beta \leq 1$ and $\mathsf{m}(n)$ is the symbol transmitted in epoch $[2nT_{sym}, (2n+1)T_{sym})$. Note that the sampling interval $T_s = T_c/2$ corresponds to an oversampling rate of two for zero percent excess bandwidth. The binary sequence $\mathbf{d}_{\mathsf{m}(n)}$ is defined by

$$\mathbf{d}_{\mathsf{m}} = \mathbf{w}_{\mathsf{m}} \otimes \mathbf{c} \in \{\pm 1\}^{N_W L_{pn}}, \tag{2}$$

where $\mathbf{w}_{\mathsf{m}}$ is the m-th row of an $N_w \times N_w$ binary Walsh matrix and $\otimes$ is the Kronecker product. The UCSB modem uses $N_w = 8$ yielding 3 bits/symbol. The m-sequence $\mathbf{c}$ is fixed for all symbols and given by $\mathbf{c} = [11-11-1-1-1]^T$. It is important to note that (1) includes a T_{sym} long channel-clearing (time-guard) interval, so that multipath spreads of up to 11.2 ms. can be tolerated without equalization. Based on the signal definition (1), it is seen that 3 bits are transmitted every $2T_{sym} = 22.4$ ms. yielding a bit rate of 133 bps. This rate is adequate for many eco-sensing and UUV control/low data-rate applications, and compares favorably with the 80 bps offered by the WHOI Micromodem in FSK/FH mode [11].

The received waveform in the presence of Doppler shift and multipath is represented by

$$r(t) = \sum_{p=1}^{N_\alpha} \alpha_p(n) e^{-i2\pi f_c t v(p)/c_s} s_{\mathsf{m}(n)}((1 - v(p)/c_s)t - \tau_p(n)) + n(t), \tag{3}$$

where

$$s_{\mathsf{m}(n)}(t) = \sum_{i=0}^{N_w L_{pn}-1} (\mathbf{d}_{\mathsf{m}(n)})_i g(t - iT_c), \tag{4}$$

and $n(t) \in \mathbb{C}$ is additive wideband receiver/ambient noise. The path delays are represented by $\tau_p(n)$. The multipath spread $\max_p \tau_p(n) - \min_p \tau_p(n)$ is assumed to be $< T_{sym}$. Note that $L_{pn} = T_{sym}/T_c$ is the number of chips/symbol, or processing gain. The Doppler velocity for path p is $v(p)$ m/s and corresponds to radial relative platform velocity for the $p = 1$ direct path. Eq. (3) includes both a residual carrier Doppler, with f_c the carrier frequency and $f_c v(p)/c_s$ the residual offset after quadrature downconversion. The code Doppler is represented by the time-compression factor $(1 - v(p)/c_s)$, which can be significant for fast UUVs. For example, let $v(p) = 10$ m/s., then $(1 - v(p)/c_s)T_{sym} = 11.12$ m/s. For $T_c = .2$ m/s, this corresponds to a time-compression of almost half a chip, which can greatly reduce the SNR of a typical RAKE receiver that ignores code Doppler. At $v(p) = 10$ m/s, the residual carrier Doppler for a $f_c = 25$ kHz center frequency is 166 Hz., which clearly must be tracked and compensated for.

A discrete-time signal model is next obtained to facilitate the GMHT-MP receiver derivation. The path delays are quantized to $T_s/4$, and $r(t)$ is sampled at T_s s. intervals. Let $N_s = T_{sym}/T_s$ be the number of Nyquist samples/symbol. The tapped-delay line multipath channel approximate coefficients are $f_l \in \mathbb{C}$. Then the vector of Nyquist samples during the n-th symbol epoch, $[2nT_{sym}, 2(n+1)T_{sym})$ is approximately

$$\mathbf{r}(n) \approx \sum_{l=0}^{N_s-1} f_l \mathbf{s}^d_{\mathsf{m}(n)}(l, v(l)) + \mathbf{n}(n), \tag{5}$$

where $\mathbf{r}(n) \in \mathbb{C}^{2N_s}$ is

$$\mathbf{r}(n) = [r((4nN_s - 1)T_s) r((4nN_s - 2)T_s) \ldots r(2nN_sT_s)]^T. \tag{6}$$

The signal vector $\mathbf{s}^d_{\mathsf{m}(n)}(l, v) \in \mathbb{C}^{2N_s}$ corresponds to the delayed and Doppler-compressed/shifted signal components in (3), and thus

$$\begin{aligned} &\mathbf{s}^d_{\mathsf{m}(n)}(l, v) = \\ &\quad [e^{-i2\pi(2N_s)f_c v/c_s} s_{\mathsf{m}(n)}(((1 - v/c_s)(2N_s - 1) - l)T_s) \\ &\quad e^{-i2\pi(2N_s-1)f_c v/c_s} s_{\mathsf{m}}(((1 - v/c_s)(2N_s - 2) - l)T_s) \ldots e^{-i2\pi f_c v/c_s} s_{\mathsf{m}(n)}(0)]^T. \end{aligned} \tag{7}$$

Both the channel coefficients $f_l(n)$ and Doppler velocities $v(l)$ must be estimated for demodulation. However, Doppler spreads of .5 Hz and greater have been reported even for stationary acoustic telemetry systems. Furthermore, the effective measurement model (5) is a highly nonlinear function of the Doppler velocities and multipath, and thus algorithms such as the extended Kalman/Gaussian Sum filter are required for channel tracking. Typical Kalman filtering approaches will also result in channel overparameterization, as they ignore the sparse nature of many UWA channels. The combination of rapidly time-varying parameters and difficulties of nonlinear estimation lead to consideration of a simpler GMHT demodulation approach, which only assumes a stationary channel over $2T_{sym} = 22.4$ ms. The Generalized Multiple Hypothesis Test demodulator is

$$\hat{\mathsf{m}} = \arg\min_{\mathsf{m}} \left\{ \min_{\mathbf{f}, \mathbf{v}: |\mathbf{f}| = N_f} ||\mathbf{r} - \mathbf{S}^d_{\mathsf{m}}(\mathbf{v})\mathbf{f}||^2 \right\}, \tag{8}$$

where $\mathbf{f} = [f_0 f_1 \ldots f_{N_s-1}]^T$, and $\mathbf{v} = [v(0)v(1) \ldots v(N_f - 1)]$ is the vector of path velocities. The constraint $|\mathbf{f}| = N_f$ indicates that at most $N_f << N_s$ elements of $\mathbf{f}$ are nonzero. The signal matrix $\mathbf{S}^d_n(\mathbf{v}) \in \mathcal{C}^{2N_s \times N_s}$ is

$$\mathbf{S}_{\mathsf{m}} = \left[\mathbf{s}^d_{\mathsf{m}}(0, v(0)) \mathbf{s}^d_{\mathsf{m}}(1, v(1)) \ldots \mathbf{s}^d_{\mathsf{m}}(N_s - 1, v(N_s - 1)) \right]. \tag{9}$$

The exact GMHT in (8) requires exhaustive search over the joint Doppler velocities $\mathbf{v}$ and all $\begin{pmatrix} N_s \\ N_f \end{pmatrix}$ numerosity $|\mathbf{f}| = N_f$ hypotheses. The exponential complexity of this joint estimation is clearly impractical and suggests the MP approach in the next Section.

GMHT-MP RECEIVER WITH DOPPLER ESTIMATION

The Matching Pursuits algorithm is described by successive cancellation and single-path ML estimation of $f_l, v(l)$. A separate MP algorithm is carried out for each data hypothesis m. The canceled signal is initialized to $\mathbf{r}^1 = \mathbf{r}$. The first such MP step sets q_1 to the index i that yields the minimum single-path residual.

$$q_1 = \arg\min_i \left\{ \min_{v(i), f_i} ||\mathbf{r}^1 - \mathbf{s}^d_{\mathsf{m}}(i, v(i)) f_i||^2 \right\}. \tag{10}$$

That is, the first detected path corresponds to the path index i, coefficient f_i and velocity $v(i)$ that best fits the received vector $\mathbf{r}$. The velocities $v(i)$ are quantized to Q values, $v_1, v_2, \ldots, v_Q$, and it is well known that the estimation of f_i and $v(i)$ is separable. Hence q_1 is equivalently

$$q_1 = \arg\max_i \max_{v_l} \frac{|\mathbf{r}^H \mathbf{s}^d_{\mathsf{m}}(i, v_l)|^2}{||\mathbf{s}^d_{\mathsf{m}}(i, v_l)||^2}. \tag{11}$$

The corresponding estimates are then

$$\hat{f}_{q_1} = \frac{1}{||\mathbf{s}^d_{\mathsf{m}}(q_1, \hat{v}(q_1))||^2} \mathbf{s}^d_{\mathsf{m}}(q_1, \hat{v}(q_1))^H \mathbf{r}, \tag{12}$$

where

$$\hat{v}(q_1) = \arg\max_{v_k} \frac{|\mathbf{r}^H \mathbf{s}^d_{\mathsf{m}}(q_1, v_k)|^2}{||\mathbf{s}^d_{\mathsf{m}}(q_1, v_k)||^2}. \tag{13}$$

The MP algorithm next computes the canceled vector

$$\mathbf{r}^2 = \mathbf{r}^1 - \mathbf{s}^d_{\mathsf{m}}(q_1, \hat{v}(q_1)) \hat{f}_{q_1}, \tag{14}$$

and steps (11),(12) and (13) are repeated using the canceled waveform $\mathbf{r}^2$, for all indices $i \neq q_1$. The overall GMHT-MP algorithm is summarized in Table 1. Note that the final symbol decision is equivalent to the GMHT rule eq. (8) with the conditional ML channel/velocity estimates replaced by the Matching Pursuits quantities. That is

$$\hat{\mathsf{m}} = \arg\min_{\mathsf{m}} ||\mathbf{r}^{N_f+1}_{\mathsf{m}}||^2 = \arg\min_{\mathsf{m}} ||\mathbf{r} - \sum_{k=1}^{N_f} \mathbf{s}^d_{\mathsf{m}}(q_k, \hat{v}(q_k)_{\mathsf{m}})(\hat{f}_{q_k})_{\mathsf{m}}||^2. \tag{15}$$

RESULTS AND CONCLUSIONS

The GMHT-MP algorithm was simulated using random circular Gaussian channel realizations on each symbol for the $\{\alpha_p\}$. The delays τ_p were sampled uniformly in $[0, T_{sym}]$ for each

For $\mathsf{m} = 1, 2, \ldots N_W$

  Get current received vector $\mathbf{r}$

  $\mathbf{r}_{\mathsf{m}}^1 = \mathbf{r}$

  Initialize channel estimate $\hat{\mathbf{f}}_{\mathsf{m}} = \mathbf{0}$

  For $k = 1, 2, \ldots, N_f$

$$q_k = \arg\max_{i \neq q_1, \ldots, q_{k-1}} \left\{ \max_{v_l} \frac{1}{||\mathbf{s}_{\mathsf{m}}^d(i, v_l)||^2} |(\mathbf{r}_{\mathsf{m}}^k)^H \mathbf{s}_{\mathsf{m}}^d(i, v_l)|^2 \right\}$$

$$\hat{v}(q_k)_{\mathsf{m}} = \arg\max_{v_l} \frac{1}{||\mathbf{s}_{\mathsf{m}}^d(q_k, v_l)||^2} |(\mathbf{r}_{\mathsf{m}}^k)^H \mathbf{s}_{\mathsf{m}}^d(q_k, v_l)|^2$$

$$(\hat{\mathbf{f}}_{\mathsf{m}})_{q_k} = \frac{1}{||\mathbf{s}_{\mathsf{m}}^d(q_k, \hat{v}(q_k))||^2} \mathbf{s}_{\mathsf{m}}^d(q_k, \hat{v}(q_k))^H \mathbf{r}_{\mathsf{m}}^k$$

$$\mathbf{r}_{\mathsf{m}}^{k+1} = \mathbf{r}_{\mathsf{m}}^k - \mathbf{s}_{\mathsf{m}}^d(q_k, \hat{v}(q_k)_{\mathsf{m}})(\hat{\mathbf{f}}_{\mathsf{m}})_{q_k}$$

  Next k

Next m

Make transmitted symbol decision using GMHT

$\hat{\mathsf{m}} = \arg\min_{\mathsf{m}} ||\mathbf{r}_{\mathsf{m}}^{N_f+1}||^2$

Table 1: GMHT-MP Algorithm for the UWA modem.

symbol, corresponding to a maximum multipath spread of 10 ms. Fig. 1 shows the multipath intensity profile (MIP) for the actual channel using sinc function interpolation, and the corresponding estimated MIP for one realization. In this case, $N_\alpha = 4$ and $N_f = 6$ corresponding to overparameterization of the channel estimate. The velocity estimates associated with the estimated paths are illustrated in Fig. 2, for $v(0) = 5$ m/s direct-path velocity. The estimated velocities $\hat{v}(p_k)$ are close to the true $v(p_k)$, except for the two spurious paths detected due to overparameterization.

The symbol error-rate was evaluated in Fig. 3 via simulation for the same random channel conditions in Fig. 1,2. The GMHT-MP receiver yields useable SERs of $\approx 1 \times 10^{-2}$ at an SNR of $E_b/N_0 = 18$ dB. In contrast, a conventional RAKE receiver without Doppler estimation/compensation yields a SER approaching unity, as the carrier Doppler alone significantly degrades RAKE correlator SNR.

To summarize, a Walsh/m-sequence waveform was designed for UUV acoustic communications that is simultaneously wideband for anti-multipath and relatively easy to demodulate. The Matching Pursuits algorithm was employed to jointly estimate Doppler shift and the sparse multipath channel. MP was embedded in a Generalized Multipath Hypothesis Test yielding a GMHT-MP receiver that far outperformed a conventional RAKE lacking Doppler compensation. Future work will focus on speeding up the exhaustive Doppler velocity search in MP and exploiting the longer-term stability of the Doppler velocity.

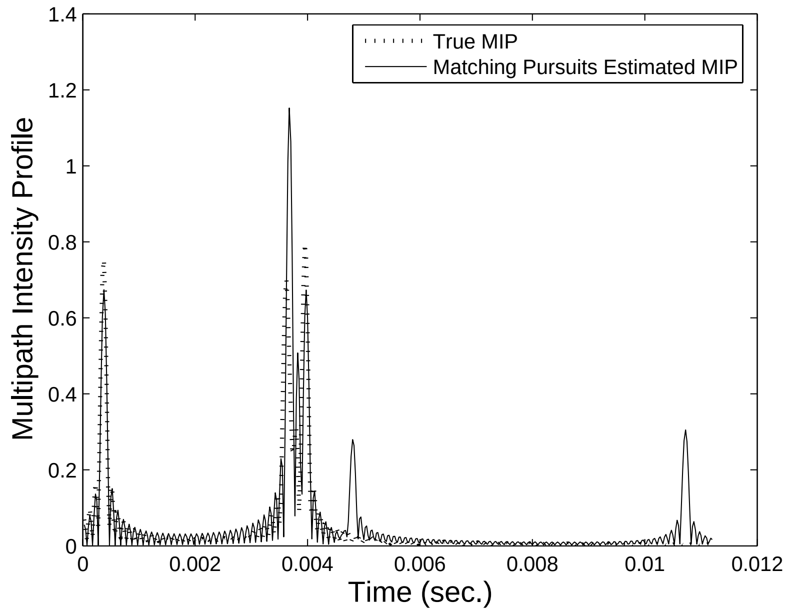

Figure 1: MP channel estimates for $N_\alpha = 4, N_f = 6$ and $E_b/N_0 = 20$ dB.

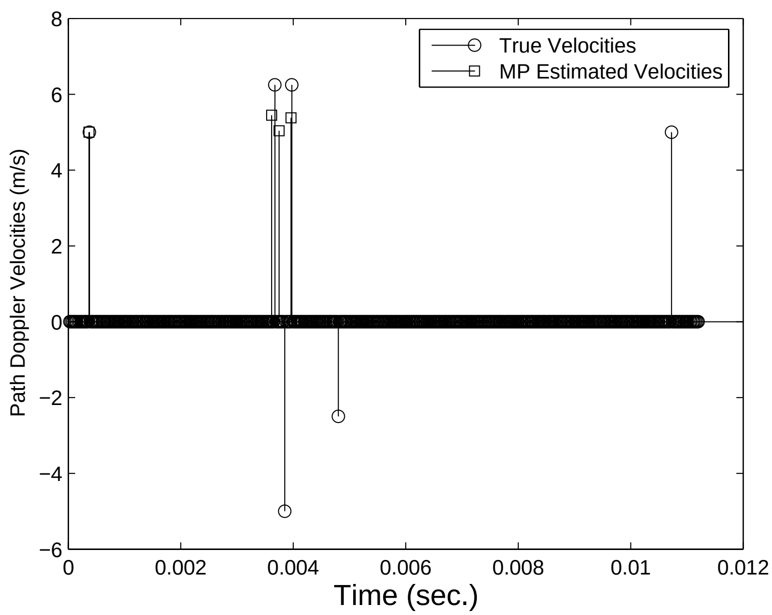

Figure 2: MP velocity estimates for $N_\alpha = 4, N_f = 6$ and $E_b/N_0 = 20$ dB, true $v = 5$ m/s.

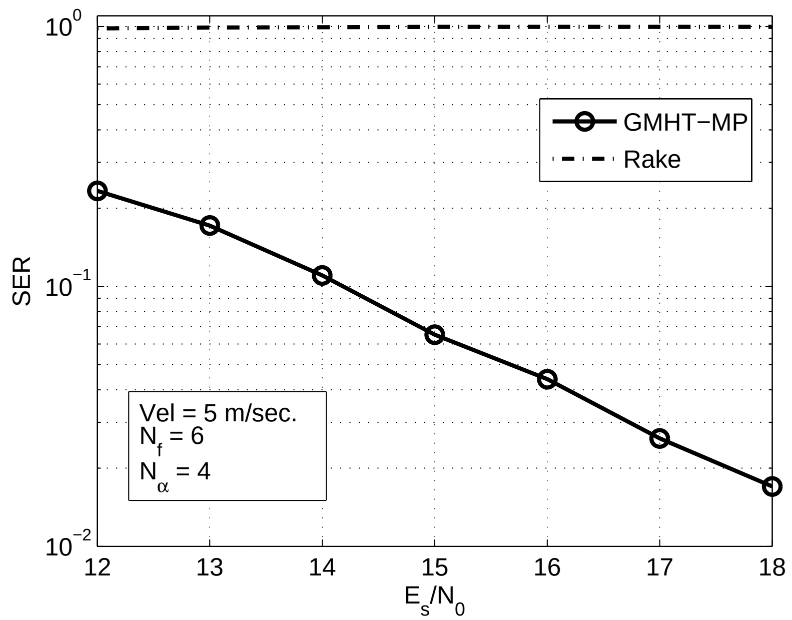

Figure 3: SERs for $N_\alpha = 4, N_f = 6$ and true $v = 5$ m/s.

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