Channel Estimation with Scale-Lag Diversity for Underwater Acoustic Communication Systems

Peng Chen
School EECMS, *Curtin University*, Bentley, WA, Australia
peng.chen@curtin.edu.au

Yue Rong
School EECMS, *Curtin University*, Bentley, WA, Australia
y.rong@curtin.edu.au

Abstract—In underwater acoustic channels, mobility induces scale spreading rather than conventional frequency spreading which is an essential assumption of narrowband systems. In such channels, multiple replicas of the transmitted signal with different scaling and delay are received and combined at the receiver. A time–scale characterization for this type of channel was proposed, and a scale-lag rake receiver for wideband direct-sequence spread-spectrum (DSSS) systems has been explored in prior work. However, practical channel estimation for time–scale models remains insufficiently addressed. This paper proposes an m-sequence-based DSSS system that multiplexes pilot and data streams, enabling channel estimation and equalization under a time–scale channel model. Experimental validation is conducted in a water tank, and the results demonstrate the performance of the proposed approach.

Index Terms—Channel estimation, time-varying channel, Underwater acoustic communication

I. INTRODUCTION

Wideband communication system is a system whose ratio of the single-sided bandwidth to center frequency exceeds 0.20. It behaves much differently from the narrowband systems under time-varying channels. When the signal time–bandwidth product is small, as in narrowband systems, or motion is sufficiently slow, the Doppler scaling can be approximated as frequency shifts. However, this approximation breaks down in wideband systems. [1] proposed a model to present these wideband mobile channels in the delay-scale domain. In this case, the system output can be represented as a superposition of time-shifted and scale-transformed replicas of the transmitted signal, weighted by a wideband spreading function.

A wideband direct-sequence spread-spectrum (DSSS) scale–lag rake receiver has been proposed in [2] based on the above model, where mobility manifests primarily as time-domain scale spreading rather than conventional frequency-domain Doppler spreading. However, practical channel estimation methods compatible with time–scale channel models remain limited.

This paper proposes an m-sequence-based DSSS system that multiplexes pilot and data streams to enable channel estimation under a time–scale characterization of wideband mobile channels. The pilot stream is designed to support estimation of the scale–lag channel parameters required for the channel equalisation. Experimental validation is conducted in a water tank, and system performance results are presented.

II. SYSTEM MODEL

We consider a multi-stream wideband DSSS system in which pilot and data streams are transmitted in parallel. The transmitted signal $s(t)$ is formed by linearly modulating the data and pilot symbol sequences using different wideband signature waveforms as

$$s(t) = \sum_{k=0}^{N_s-1} \left[s_{d,k} x_d(t - kT_s) + s_{p,k} x_p(t - kT_s) \right] \quad (1)$$

where N_s denotes the number of transmitted symbols of both data stream and pilot stream, T_s is the symbol interval, $s_{d,k}$, $k = 0, 1, 2, \cdots, N_s-1$ and $s_{p,k}$, $k = 0, 1, 2, \cdots, N_s-1$ are the kth data symbol and pilot symbol, respectively, and $x_d(t)$ and $x_p(t)$ are the DSSS sinature waveform for the data and pilot streams.

Each wideband signature waveform is constructed from a pseudo-noise (PN) chip sequence as

$$x_d(t) = \frac{1}{\sqrt{N_c}} \sum_{i=0}^{N_c-1} c_{d,i} p(t - iT_c) \quad (2)$$

$$x_p(t) = \frac{1}{\sqrt{N_c}} \sum_{i=0}^{N_c-1} c_{p,i} p(t - iT_c) \quad (3)$$

where $p(t)$ is the unit-energy chip pulse, T_c is the chip interval, and $c_{d,i}$, $i = 0, \cdots, N_c - 1$ and $c_{p,i}$, $i = 0, \cdots, N_c - 1$ are length-N_c PN sequences associated with the data and pilot streams, respectively.

The PN sequences are generated by appending a cyclic prefix of length N_{cp} to the base sequences $\bar{\mathbf{c}}_d$ and $\bar{\mathbf{c}}_p$, which are of the same length $N_c' = N_c - N_{cp}$, so that

$$c_{d,i} = \begin{cases} \bar{c}_{d,N_c'-N_{cp}+i}, & 0 \le i < N_{cp} \\ \bar{c}_{d,i-N_{cp}}, & N_{cp} \le i < N_c \end{cases} \quad (4)$$

$$c_{p,i} = \begin{cases} \bar{c}_{p,N_c'-N_{cp}+i}, & 0 \le i < N_{cp} \\ \bar{c}_{p,i-N_{cp}}, & N_{cp} \le i < N_c \end{cases} \quad (5)$$

The sequence $\bar{\mathbf{c}}_d$ is selected as an m-sequence, while $\bar{\mathbf{c}}_p$ is a circularly shifted version of $\bar{\mathbf{c}}_d$ by N_{shift} chips. Due to the correlation properties of m-sequences, the circular cross-correlation between $\bar{\mathbf{c}}_d$ and $\bar{\mathbf{c}}_p$ is approximately $\frac{1}{N_c'}$ except at the shift position. We select $N_c' = 2N_{shift} + 1$ and a
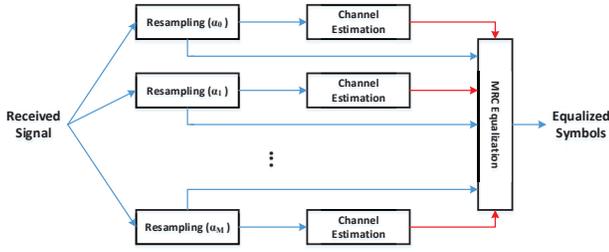
Fig. 1. Block-diagram for the proposed scale-lag rake receiver.

TABLE I
EXPERIMENTAL SYSTEM PARAMETERS.

bandwidth	4 kHz
carrier frequency	12 kHz
sampling rate	96 kHz
CP length (N_{cp})	80
m-sequence length (N_c')	255
DSSS sequence length (N_c)	335
symbole number (N_s)	9,000
modulation type	QPSK

Fig. 2. Power of channel estimated by the delay rake receiver.
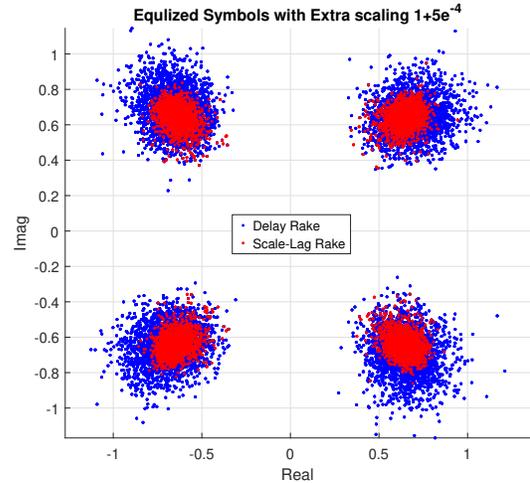
Fig. 3. Performance of the proposed receiver.

sufficiently large N_c' so that N_{shift} is larger than the maximum channel delay spread.

The received signal $r(t)$ is modelled using a wideband time-varying channel representation,

$$r(t) = \iint \mathcal{H}(a,\tau) \frac{1}{\sqrt{a}} s\left(\frac{t-\tau}{a}\right) da\, d\tau + w(t) \qquad (6)$$

where $\mathcal{H}(\alpha,\tau)$ denotes the wideband channel kernel, and $w(t)$ is zero-mean additive white Gaussian noise (AWGN) with power spectral density δ_w^2. In this model, the kernel $\mathcal{H}(\alpha,\tau)$ characterizes the aggregate contribution of propagation paths associated with delay τ and scaling factor α, capturing wideband time and frequency doubly selective fading effects. The proposed scale-lag rake receiver based on [2] is demonstrated in Fig. 1.

III. EXPERIMENTAL RESULTS

An underwater acoustic communication experiment was conducted in a tank at Curtin University to compare the performance of the proposed scale-lag rake receiver with the traditional delay rake receiver. The key waveform parameters are summarized in Table I. Both the transducer and the hydrophone are placed in a tank whose length, width, and depth are 2.5 m, 1.5 m, and 1.8 m, respectively. The transducer was positioned at a depth of 0.8 m at the corner of the tank, while the hydrophone was mounted on a metal rod and continuously moved during the experiment, with an approximate depth of 0.55 m.

Fig. 2 shows the normalized l_2-norm of the channel estimation results of the delay rake receiver, which characterizes the time-varying behavior of the wideband mobile channel. The dominant propagation path exhibits noticeable drift over time, with its delay varying approximately from 7 ms to 12 ms. Thanks to the confined ta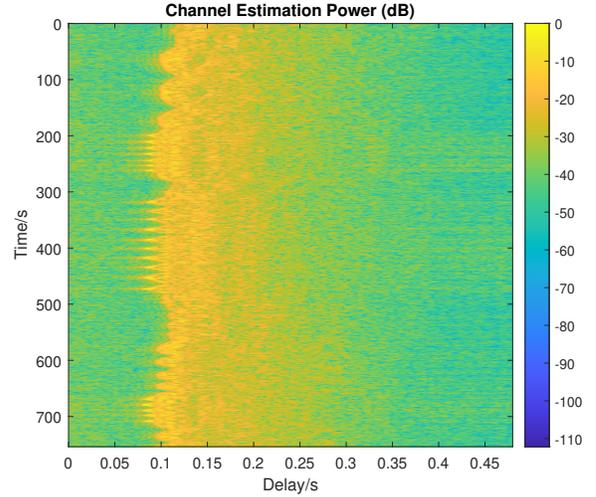nk environment and strong boundary reflections, multiple propagation paths are observed, and the maximum excess delay of the channel is approximately 20 ms.

The variation rate of the channel shown in Fig. 2 is limited due to the tank dimensions. To enable performance comparison, a residual scaling factor of $1+5e^{-4}$ was applied to the received signal to emulate imperfect scale compensation in practical systems. As shown in Fig. 3, the proposed scale–delay rake receiver yields more compact equalized symbol clusters than the conventional delay rake receiver, indicating improved robustness to scale distortion.

REFERENCES

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