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Selected-Mapping Peak-to-Average Power Reduction Method with Orthogonal Pilot Sequences in Underwater Acoustic OFDM System Without Side Information

QIAO Gang[1,2,3], XING Siyu[1,2,3] and ZHOU Feng[1,2,3]

(1. *Acoustic Science and Technology Laboratory, Harbin Engineering University, Harbin 150001, China*)

(2. *Key Laboratory of Marine Information Acquisition and Security* (*Harbin Engineering University*), *Ministry of Industry and Information Technology, Harbin 150001, China*)

(3. *College of Underwater Acoustic Engineering, Harbin Engineering University, Harbin 150001, China*)

Abstract — A novel Selected-mapping (SLM) Peak-to-average power ratio (PAPR) reduction scheme requires no Side information (SI) in Underwater acoustic (UWA) OFDM system is proposed. In the proposed scheme, every distinct phase sequence is represented by a unique Orthogonal comb pilot sequence (OPS), and the orthogonal properties of the OPSs are used to distinguish the index of phase sequences at the receiver. Therefore, the proposed scheme does not need to reserve bits for transmitting SI, so that the data rate can be raised. Simulation results show that the PAPR reduction performance has almost 0.5dB gains comparing to the Conventional SLM (C-SLM) scheme and the Bit error ratio (BER) performance is approximately the same as the SLM scheme with perfect SI. Field experimental results also demonstrate that the proposed scheme can differentiate phase sequences, therefore significantly enhance the quality of the UWA OFDM communication system.

Key words — Underwater acoustic communication, OFDM, PAPR reduction, Selected mapping.

I. Introduction

The shallow Underwater acoustic (UWA) channel is regarded as the most difficult wireless communication channel due to its complex environment. Orthogonal frequency division multiplexing (OFDM) has been widely studied in UWA communication system because of its high spectrum efficiency and good performance in anti-multipath[1−3]. However, OFDM system suffers several drawbacks, such as high Peak-to-average power ratio (PAPR). Therefore, many PAPR reduction schemes have been proposed[4,5]. Selected mapping (SLM) is a widely adopted scheme without signal distortion[6]. However, the index of the selected phase sequence must be transmitted as Side information (SI) precisely. Otherwise, it will lead to data rate losing and communication quality decreasing.

Several proposals suggested using the cyclic shift and linear combining to generate an SLM scheme without SI, however, the BER performance is decreased[7,8]. Some researchers suggested pilot-symbol aid approaches which allow blind detection, while losing part of PAPR reduction performance or decreasing the band efficiency[9,10]. Another no SI SLM scheme with low-complexity requires Channel state information (CSI) as prior information, which makes it not appropriate for UWA communication[11].

In this paper, we proposed a novel SLM scheme with Orthogonal comb pilot sequences (OPS) to reduce the PAPR in UWA OFDM system. The proposed scheme uses a unique OPS to represent every distinct phase sequence and conducts blind detection by the orthogonal properties of the OPSs. Therefore, the novel scheme has better PAPR reduction performance owing to the randomness brought by the OPS. Furthermore, the proposed SLM scheme avoids any loss of data rate and BER performance.

II. System Model

The proposed scheme utilizes different OPS to represent different phase sequences and transmit the

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OFDM symbol with the minimum PAPR. The main part of the receiver is the phase sequence detector, which utilizes the orthogonal properties of the OPSs to differentiate the index of the OPSs while completing the channel estimation. According to the correspondence between the OPSs and the phase sequences, which phase sequence was selected at the transmitter can be known. The framework of the novel SLM scheme is shown in Fig.1.

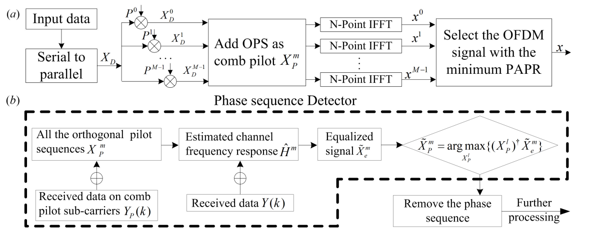

Fig. 1. Framework of the novel SLM cheme in UWA OFDM system. (a) Framework of the transmitter; (b) Framework of the receiver

III. Proposed SLM Scheme

Take one symbol as an example to explain the principle of the proposed SLM scheme. The total number of sub-carriers is N, and the number of pilot tones is N_p. Denote $\boldsymbol{Po} = \{i_0, i_1, \cdots, i_{N_p-1}\}$ as the index of pilot tones and $\boldsymbol{Po}^c$ as the complementary set of $\boldsymbol{Po}$ in $\boldsymbol{R} = [0, 1, \cdots N-1]$, represents the data symbols index. The input data block $\boldsymbol{X}_D = [X_D(0), X_D(1), \cdots, X_D(N-1)]$ is multiplied by M different phase sequences $\boldsymbol{P}^m = [P^m(0), P^m(1), \cdots, P^m(N-1)], 0 \leq m \leq M$, which produce a set of modified data blocks $\boldsymbol{X}_D{}^m = \boldsymbol{P}^m \boldsymbol{X}_D$.

Define M different OPS corresponding to different phase sequences $\boldsymbol{X}_P^m = [X_P^m(0), X_P^m(1), \ldots, X_P^m(N-1)]$. The pilot sequence has N_p free parameters chosen from $\{1, -1\}$, and the value M is then limited to be $M \leq N_p$. The well-known Walsh-Hadamard sequences is chosen as the OPSs. Therefore, the OFDM symbol in the frequency domain can be represented as

$$X^m(k) = X_D^m(k) + X_P^m(k) = \begin{cases} X_D^m(k)\ ,\ k \in \boldsymbol{Po}^C \\ X_P^m(k)\ ,\ k \in \boldsymbol{Po} \end{cases} \tag{1}$$

The signal in time domain can be written as

$$\boldsymbol{x}^m = \boldsymbol{F}^\dagger \boldsymbol{X}^m = \boldsymbol{F}^\dagger(\boldsymbol{X}_D^m + \boldsymbol{X}_P^m) \tag{2}$$

The matrix $\boldsymbol{F}$ represents the IFFT operation, and the superscript $(\bullet)^\dagger$ denotes the Hermitian conjugate. The only one $\tilde{\boldsymbol{x}}^m$ with the lowest PAPR can be selected by

$$\tilde{\boldsymbol{x}}^m = \arg\min_{\boldsymbol{x}^m}\{\frac{\max(|x^m[k]|^2)}{\varepsilon\{|x^m[k]|^2\}}\} \tag{3}$$

The selected OFDM symbol $\tilde{\boldsymbol{x}}^m$ is the transmitted signal. The only difference of the transmitter is the employment of the OPS.

At the receiver, after taking the FFT operation, the received signal in frequency domain can be given as

$$\boldsymbol{Y} = \boldsymbol{HX} + \boldsymbol{W} \tag{4}$$

where $\boldsymbol{H}$ and $\boldsymbol{W}$ denote the frequency response of the UWA channel and the white Gaussian noise respectively. Denote $\hat{\boldsymbol{H}}^m$ as the estimation of $\boldsymbol{H}$, the sampling value of $\hat{\boldsymbol{H}}^m$ can be achieved by $\hat{\boldsymbol{H}}_P^m = \boldsymbol{Y}_P / \boldsymbol{X}_P^m$, while $\hat{\boldsymbol{H}}^m$ can be got by some interpolation schemes. The equalized signal $\tilde{\boldsymbol{X}}_e^m$ can be obtained by

$$\begin{aligned} \tilde{\boldsymbol{X}}_e^m &= (\hat{\boldsymbol{H}}^m)^{-1}\boldsymbol{Y} \\ &= (\hat{\boldsymbol{H}}^m)^{-1}\boldsymbol{H}^m\boldsymbol{X} + (\hat{\boldsymbol{H}}^m)^{-1}\boldsymbol{W}^m \\ &= \Delta\boldsymbol{H}^m(\boldsymbol{H}^m)^{-1}\boldsymbol{H}^m X + (\hat{\boldsymbol{H}}^m)^{-1}\boldsymbol{W}^m \\ &= \Delta\boldsymbol{H}^m(\boldsymbol{X}_D^m + \boldsymbol{X}_P^m) + \overline{\boldsymbol{W}^m} \end{aligned} \tag{5}$$

with a zero-forcing criterion, where the vector $\overline{\boldsymbol{W}^m}$ contains uncorrelated noise samples. As the OPS are orthogonal, the detection of selected phase pattern can be carried out with a simple decision rule as follow, based on maximizing the correlation between the equalized signal and the M possible orthogonal pilot sequences $\boldsymbol{X}_P^l$.

$$\tilde{\boldsymbol{X}}_P^m = \arg\max_{\boldsymbol{X}_P^l}\{(\boldsymbol{X}_P^l)^\dagger \tilde{\boldsymbol{X}}_e^m\} \tag{6}$$

where

$$\begin{aligned} (\boldsymbol{X}_P^l)^\dagger \tilde{\boldsymbol{X}}_e^m &= (\boldsymbol{X}_P^l)^\dagger[\Delta\boldsymbol{H}^m(\boldsymbol{X}_D^m + \boldsymbol{X}_P^m)] + (\boldsymbol{X}_P^l)^\dagger\overline{\boldsymbol{W}^m} \\ &= (\boldsymbol{X}_P^l)^\dagger\Delta\boldsymbol{H}^m\boldsymbol{X}_D^m + (\boldsymbol{X}_P^l)^\dagger\Delta\boldsymbol{H}^m\boldsymbol{X}_P^m + (\boldsymbol{X}_P^l)^\dagger\overline{\boldsymbol{W}^m} \end{aligned} \tag{7}$$

The decision rule can be simplified as

$$(\boldsymbol{X}_P^l)^\dagger \tilde{\boldsymbol{X}}_e^m = (\boldsymbol{X}_P^l)^\dagger \boldsymbol{X}_P^m + (\boldsymbol{X}_P^l)^\dagger(\hat{\boldsymbol{H}}^m)^{-1}\boldsymbol{W}^m \tag{8}$$

Due to the orthogonal properties of the OPSs, we have

$$(\boldsymbol{X}_P^l)^\dagger \boldsymbol{X}_P^m = \begin{cases} N_p, \boldsymbol{X}_P^l = \boldsymbol{X}_P^m \\ 0, \quad \boldsymbol{X}_P^l \neq \boldsymbol{X}_P^m \end{cases} \tag{9}$$

So that the one which makes $\tilde{\boldsymbol{X}}_P^l = \boldsymbol{X}_P^m$ is the selected OPS at the transmitter. The corresponding phase sequence $\boldsymbol{P}^l$ is the answer we are looking for.

IV. Simulation and Experimental Results

1. Simulation results

The parameters of the UWA system are given in Table 1, and the Channel impulse response (CIR) of the sparse channel adopted in simulations is illustrated in Fig.2.

Complementary cumulative distribution function (CCDF) is used to measure the PAPR reduction performance. The comparisons of the performance between the C-SLM and the proposed scheme are given in Fig.3. It can be seen that the proposed scheme has nearly 0.5dB gains because of the randomness brought by the OPSs. Fig.3 (b) stated the BER performance comparison. In the C-SLM scheme, the error probability of SI P_s can be regarded as equal as the BER of data symbol with perfect SI (P_b). The BER performance of the proposed scheme is better than that of the C-SLM scheme, and approximately the same as the SLM scheme with perfect SI. It indicates that the proposed scheme can provide excellent SI by differentiating the selected phase sequence index exactly.

Table 1. Parameters of the UWA OFDM system

Parameters	Value	Parameters	Value
FFT length	8192	Band range	6–12kHz
Sub-carriers number	1025	Sub-carrier spacing	5.86Hz
Phase sequences number	4	Pilot spacing	4
OFDM symbol length	171ms	Sampling rate	48kHz

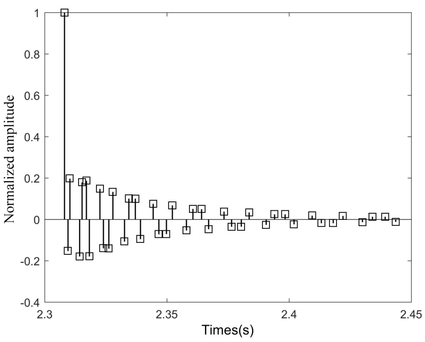

Fig. 2. The impulse response of the simulation channel

2. Field experimental results

For validating the feasibility of the proposed scheme, a field experiment was conducted at the Huanghai Sea, Qingdao, China. The depths of the transducer and receiver were 7m and 4m under the sea surface respectively and ranges for 1070m. Both boats remained in Anchorage and the sea was under a slight-sea condition during the field experiment period.

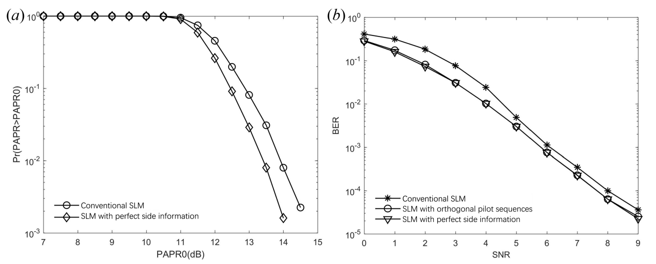

Fig. 3. Performance comparison between C-SLM and novel SLM scheme. (a) PAPR reduction performance; (b) BER performance

CIR of the field channel as a function of time are shown in Fig.4(a). Each path of the CIRs fluctuates with respect to time, due to the small waves. The estimation of the temporal coherence of the channel is shown in Fig.4(b). As the sea surface is not calm, the temporal coherence decreases rapidly, so the channel experienced by each symbol can be regarded as independent. The received Signal to noise ratio (SNR) is about 9.37dB.

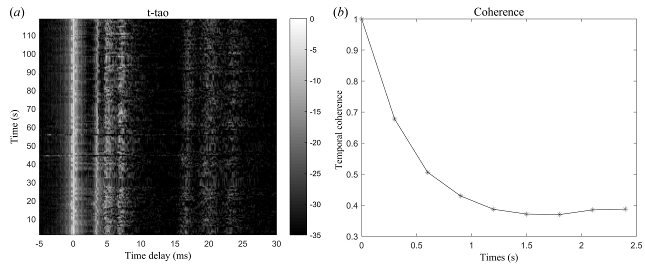

Fig. 4. (a) The CIRs of the field channel which is determined by LFM signals as a function of time; (b) The Temporal coherence of the CIRs

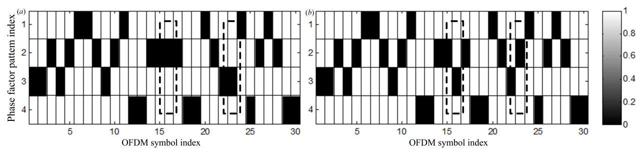

Fig. 5. The experimental result of the SI detection using the C-SLM scheme. (a) The original version of SI; (b) The decoded version of SI

Fig.5 shows the experimental result of the first 30 OFDM symbols in the transmitted signal of C-SLM scheme. Fig.5(a) is the original version of the transmitted SI, while Fig.5(b) shows the decoded version of the transmitted SI. The symbols transmitted SI share the same condition with the data symbols, which means $P_s = P_b$. The SI of the symbols in dash boxes are mistranslated, resulting in a decoding disaster because of the BER of those symbols is almost 0.5. The BER performance of the UWA OFDM system will be affected seriously.

The phase sequences index detected results of the identical 30 OFDM symbols using the novel SLM scheme are shown in Fig.6. The gradation value equals to the autocorrelation value between the selected pilot sequence and the other OPSs. Fig.6(a) is same as it is shown in Fig.5(a), and Fig.6(b) is the translated version recognized by phase sequence detector autonomously. It can be easily found that the SI of the symbols in dash boxes have been translated exactly. It verifies that the proposed scheme can differentiate among phase sequences, even if CSI and SI remain unknown.

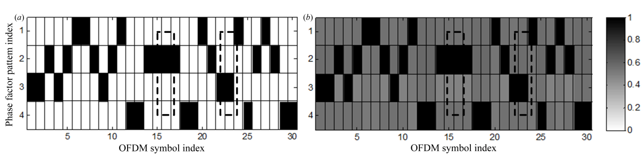

Fig. 6. The experimental result of the SI detection of the proposed SLM scheme with OPS. (a) The original version of the transmitted SI; (b) The translated version recognized by phase sequence detector

The results of transmitted figure restored by the received data after decoding are shown in Fig.7. One notices that the C-SLM scheme with the SI has the whole symbol decoding errors caused by SI mistranslating, while the proposed SLM scheme can avoid it. Therefore, the proposed SLM algorithm decreases BER more than one magnitude in comparison to the conventional one.

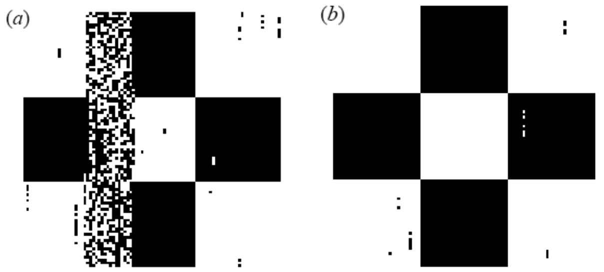

Fig. 7. The figures restored by the received decoded data. (*a*) The result of C-SLM method which transmitted SI BER = 0.0898; (*b*) The result of proposed SLM method with OPS BER = 0.0025

V. Conclusions

A novel Peak-to-Average power ratio reduction scheme that requires no SI in UWA OFDM system is proposed in this paper. A set of OPS is defined corresponding to different phase sequences in this proposed scheme. The orthogonal properties of the pilot sequences were utilized to distinguish the number of phase sequences at the receiver. The simulation and experimental results show that the proposed SLM scheme has a little bit gain in the PAPR reduction performance compared to the C-SLM and the BER performance is approximately the same as the SLM scheme with perfect SI. The proposed SLM scheme avoids any data rate loss and the whole symbol decoding errors caused by SI mistranslating. The proposed SLM scheme significantly enhances the quality of the UWA OFDM communication system.

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QIAO Gang received the Ph.D. degree in signal and information processing from the College of Underwater Acoustic Engineering, Harbin Engineering University, China. He is a professor and the Dean in the College of Underwater Acoustic Engineering at Harbin Engineering University. He is a member of Acoustical Society of China and the vice chairman of Robotics Society of Hei Longjiang Province. His current research interests include underwater communication and network, detection and positioning of underwater targets, and the sonar designed for small carriers. (Email: qiaogang@hrbeu.edu.cn)

ZHOU Feng (corresponding author) received the Ph.D. degree in signal and information processing from the College of Underwater Acoustic Engineering, Harbin Engineering University, China. He is currently an professor in the College of Underwater Acoustic at the Harbin Engineering University. His current research interests are underwater acoustic spread spectrum communications, localization in underwater networks and underwater acoustic modem development.
(Email: zhoufeng@hrbeu.edu.cn)