A Pilot-Aided Dual-Mode Multiple Sequences Spread-Spectrum System for Underwater Acoustic Communication

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***Abstract*—In the multiple sequences spread spectrum (MSSS) system, multiple cyclic shifted spreading sequences are superimposed to increase the data rate. This paper proposes a dual-mode MSSS system with index modulation aided by a secondary pilot symbol (DM-MSSS-IM) for underwater acoustic communication. The proposed system divides the bit stream into index bits and modulated bits. The modulated bits are mapped to dual-mode constellations. The index bits are used to select a place for the first modulation mode symbol. The unselected place is used to carry the second mode symbols, which is regarded as the secondary pilot symbol (SPS) to enhance channel estimation. The simulation results show that the proposed system achieves a higher data rate than the existing MSSS system over time-frequency doubly selective fading channels and underwater acoustic channels as the cost of a slight BER performance loss. Additionally, the field experiment verifies the superiority of the proposed scheme.**

***Index Terms*—Multiple Sequence Spread Spectrum, Index Modulation, Dual-Mode Modulation.**

I. Introduction

Underwater acoustic (UWA) communication has important strategic significance in national defense and civil domains, making UWA communication a preferred underwater information transmission scheme. However, the UWA channel is one of the most complex channels for its complicated multi-path, time-varying, and narrow available bandwidth properties [1], [2], which result in severe inter-symbol interference, high transmission delay, and low data rate between transmitter and receiver. The demand for reliable communication in the UWA channel is becoming increasingly urgent.

The spread-spectrum technique is extensively used in the UWA domain because of its excellent anti-multipath interference capability, low probability of intercept, and strong robustness. Direct sequence spread-spectrum (DSSS) is a well-established communication method in UWA channel [3]. The DSSS-based technique achieves long-distance transmission with strong confidentiality. Owing to the scarcely available bandwidth, DSSS is not suitable for high-speed transmission. Recent trends in DSSS-based systems have led to a proliferation of studies to enhance the data rate. A cyclic shift keying (CSK) scheme is proposed in [4]. The data rate of the CSK-DSSS system increases to $\log_2(N)$ (N is the spreading factor). Multiple sequence spread-spectrum (MSSS) is proposed in [5]. In the MSSS system, constellation symbols are spread by multiple cyclic shifted spreading sequences and then superimposed to transmit in one transmission block. The pilot symbol is spread by the original spreading sequence, contributing to better channel estimation in the time-varying channel than in the conventional DSSS system. MSSS system greatly improves the transmission data rate. However, the data rate of the MSSS-based system still has room for improvement.

The index modulation is a promising method that introduces extra modulation to improve the system performance. Several index modulation methods have been proposed for the MSSS system. An MSSS system with cyclic index modulation was proposed in [6]. The indexes of superimposed spreading sequences are used to carry extra information bits, where part of spreading sequences of available spreading sequences is activated. In [7], an MSSS system with in-phase/quadrature index modulation was proposed. In the proposed scheme, cyclic index modulation is extended to in-phase and quadrature signals, so spectral efficiency and data rate are improved.

An adaptive denoising channel estimation method is proposed by Yong-Ho Cho et al. in [8] which exploits two types of pilot symbols, namely primary pilot symbol (PPS) and secondary pilot symbol (SPS), to improve the channel estimation. Inspired by [8], this paper proposes a dual-mode MSSS system with index modulation (DM-MSSS-IM). In the proposed DM-MSSS-IM system, all cyclic spreading sequences are used to carry modulated bits. The transmitted bits are divided into index bits and modulated bits. The modulated bits are further divided into two parts. The first part maps to the constellation of mode-one and the second part maps to the constellation of mode-two. At first, the activated spreading sequence used to carry the constellation symbol of mode-two is determined by index bits. Then the remained spreading sequences are used to spread the symbols of mode-one. At the receiver, after demodulating the symbol of mode-two, the demodulated symbol is regarded as the secondary pilot symbol (SPS), which is employed to estimate the second channel impulse response (CIR). Combining channel impulse responses estimated by PPS and SPS, the DM-MSSS-IM system gains better channel estimation. The simulation results and field experiments show good performance of the DM-MSSS-IM system over MSSS and MSSS-IM systems.

II. System Model

A. Modulation Mode and Frame Structure of DM-MSSS-IM system

MSSS is abbreviated as multiple sequences spread-spectrum, in which pseudo-noise (PN) sequences with good periodic autocorrelation properties are adopted as spreading sequences. Multiple spreading sequences are cyclic shifted and superimposed in transmission.

In the existing MSSS-IM system, active spreading sequences are less than available. The inactive spreading sequences are not transmitted. The receiver distinguishes the index slot by detecting the spreading sequence with minimal energy. The index constellation occupies the inactive spreading sequence, equivalent to multiplying the active spreading sequence by zero.

The proposed DM-MSSS-IM system utilizes the spreading sequences, which is inactive in conventional MSSS-IM system, to carry SPS by employing different modulation modes for modulated bits. The bits mapped into SPS adopt a modulation mode different from other modulated bits, which makes SPS easily distinguished in the receiver. SPS provides additional information in channel estimation, contributing to a more accurate CIR estimation.

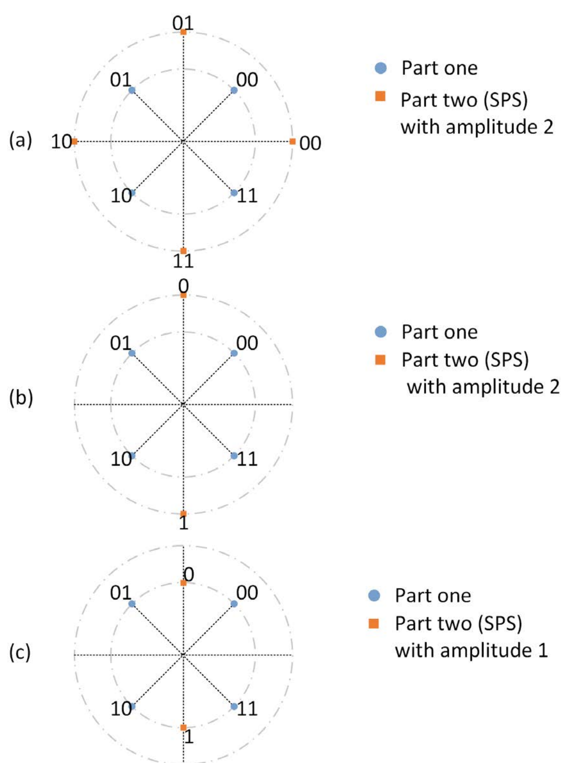

Fig. 1: The modulation modes of DM-MSSS-IM.

It is worth noting that introducing dual-mode modulation does increase data rate at the cost of deterioration of BER in low signal-to-noise(SNR) region. Inserting too many index symbols may deteriorate the BER performance because of incorrect index detection. Thus, the following article discusses the case containing only one SPS.

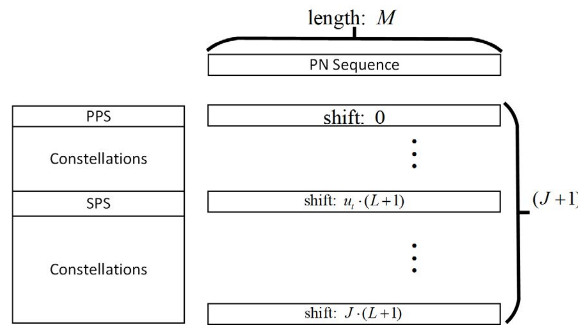

Fig. 2: The structure of a DM-MSSS-IM frame.

The modulated bits consist of two parts. The first part is the common modulated bits that adopt the standard QPSK modulation scheme. The second part adopts a modulation mode different from the former and will be mapped into SPS.

The modulation modes of the modulated bits and the frame structure of the DM-MSSS-IM system are shown in Fig.1 and Fig.2, respectively. The orange square point represents the modulation mode for the first part of modulated bits. The blue circle point represents the modulation mode for the second part of modulated bits, which will be mapped into SPS.

The modulated bits are sent to the dual-mode mapper and mapped into $(J-1)$ common constellations and one SPS for each transmission block. J is defined as the number of superimposed sequences per block upper and bounded by $J_{max} = \lfloor \frac{M}{L+1} \rfloor$. Generally, J_{max} slots containing a PPS and J constellation symbols are available in a DM-MSSS-IM transmitting block as shown in Fig.2. One slot is reserved for PPS, that is to say, $J = J_{max} - 1$. Operator $\lfloor \cdot \rfloor$ denotes the floor function.

DM-MSSS-IM system adopts PN sequence with good periodic auto-correlation properties as spreading sequence. In this study, m-sequence with length M is adopted. Defining $L = \lfloor \tau_{max}/T_c \rfloor$, where τ_{max} denotes the maximum delay spread and T_c is the chip duration, thus L represents the maximum number of chips of the maximum delay spread, which is the number of resolution multi-path. $\mathbf{T}$ is circular shift matrix defined as

$$\mathbf{T} = \begin{pmatrix} \mathbf{0}_{1\times(M-1)} & 1 \\ \mathbf{I}_{M-1} & \mathbf{0}_{(M-1)\times 1} \end{pmatrix}, \quad (1)$$

where $\mathbf{I}$ denotes identity matrix, and $\mathbf{0}_{N\times M}$ denotes $N \times M$ all 0 matrix. $\mathbf{T}$ is a $M \times M$ matrix.

B. The Transmitter

The transmitter of the DM-MSSS-IM system is illustrated in Fig.3. In the proposed system, the number of mapped bits is calculated as $g_0 = \lfloor \log_2 J \rfloor$. Assume that M_p, M_c are the modulation order for the first part of g_1 modulated bits and the second part of g_2 modulated bits, respectively. QPSK scheme is

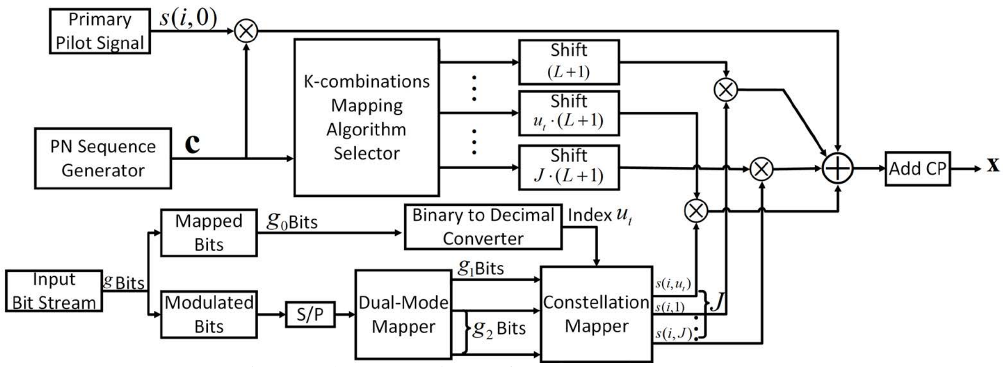

Fig. 3: The transmitter of DM-MSSS-IM system.

adopted, thus $M_c = 2$. The total number of input bits transmitted in a DM-MSSS-IM block is $g = g_0 + g_1 + g_2$, where $g_1 = M_p$, $g_2 = M_c \times (J-1)$.

$\mathbf{c}$ denotes the original spreading sequence. Input bits are divided into g_0 mapped bits and (g_1+g_2) modulated bits. Mapped bits are sent to the binary to the decimal converter, which converts mapped bits to index u_t.

The modulation mode adopted in the transmitter determines M_p of the second part modulated bits. As shown in Fig.1(a), M_p is 2, the u_t^{th} and $(u_t+1)^{th}$ bits are selected to be the second part modulated bits. For the modulation mode shown as Fig.1(b) and Fig.1(c), M_p is 1, the u_t^{th} bit is selected to be the second part modulated bits.

Modulated bits are sent to the dual-mode mapper for dual-mode modulation. g_1 first part modulated bits and g_2 second part modulated bits are modulated into $(J-1)$ common constellation symbols with mode-one and one SPS with mode-two, respectively. For the i^{th} transmitted block, denoting SPS as $s(i, u_t)$ and $(J-1)$ common constellation symbols as $\{s(i,1), \cdots, s(i,J)\}$, respectively.

Then, J constellation symbols are spread by corresponding cyclic shifted spreading sequences. The i^{th} constellation symbol is spread by PN sequence with shift length $i(L+1)$. Specially, the SPS is spread by PN sequence with shift length $u_t(L+1)$. The PPS is spread by original spreading sequenced $\mathbf{c}$ with no cyclic shift. A total of $(J+1)$ spreading sequences are superimposed in a transmitting frame. Thus, the i^{th} transmitted signal $x(i)$ can be written as

$$x(i) = \sum_{j=0}^{J} s(i,j)\mathbf{T}^{j(L+1)}\mathbf{c} \tag{2}$$

A cyclic prefix is inserted to eliminate inter-block-interference (IBI) before transmission.

C. The Receiver

It is assumed that the channel is time-invariant during a transmitting block period and time-variant between adjacent transmitting blocks. To eliminate the interference of IBI, the length of CP is $(L+1)$. The channel impulse response(CIR) can be written as

$$\mathbf{H}(i) = \sum_{l=0}^{L} h(i;l)\mathbf{T}^{l} \tag{3}$$

where $h(i;l)$ denotes the CIR of the l^{th} multi-path in the i^{th} transmitting block.

The received signal can be expressed as

$$\begin{aligned}
\mathbf{y} &= \mathbf{H}(i)\cdot\mathbf{x} + \mathbf{n} \\
&= \sum_{l=0}^{L} h(i;l)\mathbf{T}^{l} \sum_{j=0}^{J} s(i,j)\mathbf{T}^{j(L+1)}\mathbf{c} + \mathbf{n} \\
&= \sum_{j=0}^{J} s(i,j) \sum_{l=0}^{L} h(i;l)\mathbf{T}^{j(L+1)+l}\mathbf{c} + \mathbf{n} \\
&= \sum_{j=0, j\neq u_t}^{J} s(i,j) \sum_{l=0}^{L} h(i;l)\mathbf{T}^{j(L+1)+l}\mathbf{c} \\
&\quad + s(i,u_t)\sum_{l=0}^{L} h(i;l)\mathbf{T}^{u_t(L+1)+l}\mathbf{c} + \mathbf{n}
\end{aligned} \tag{4}$$

where $s(i,u_t)$ denotes the SPS, and $s(i,j), (i \neq j)$ denotes the common constellation symbols, $\mathbf{n}$ denotes the additive noise.

The DM-MSSS-IM system adopts the same matching filter as MSSS. The output of the matching filter is depicted as (i is omitted for brevity.)

$$v(j,l) = [\mathbf{T}^{j(L+1)+l}\mathbf{c}]^{\mathbf{T}} \cdot \mathbf{y} \tag{5}$$

The RAKE receiver of the DM-MSSS-IM system is illustrated in Fig.4. Channel estimation module roughly estimates each path of CIR by the PPS, denoted as $h_1(l)$.

$$h_1(l) = \frac{v(0,l)}{Ms(0)} \tag{6}$$

The despreading block 1 rectifies the received signal according to h_1, which is estimated by PPS. The PN sequence generator generates the same spreading sequences used in the transmitter. Then, J remaining spreading sequences are sent

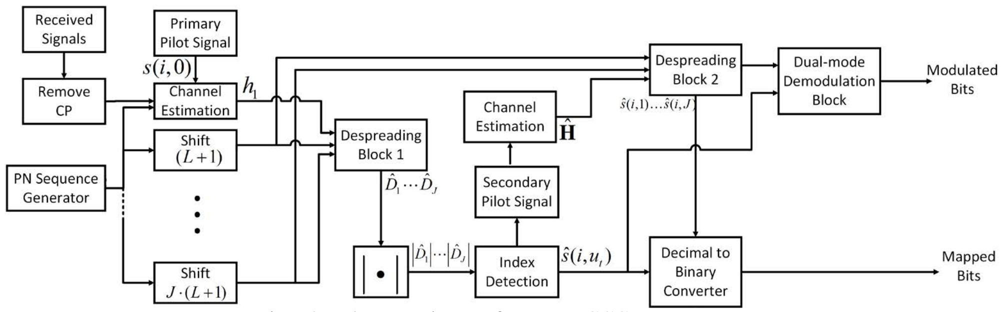

Fig. 4: The receiver of DM-MSSS-IM system.

to the despreading block 1 for correlation calculation. Hence, J constellation symbols $\{\hat{D}_1, \cdots, \hat{D}_J\}$ is obtained by roughly channel estimation based on PPS.

$$\hat{D}(j) = \frac{\sum_{l=1}^{L} \hat{h_1}^*(l)v(j,l)}{M||\hat{h_1}(l)||^2}, \tag{7}$$

where $(\cdot)^*$ denotes conjugation operator, $||(\cdot)||$ denotes 2-norm operator. The index detection block compares the absolute value of J constellation symbols $\{|\hat{D}_1|, \cdots, |\hat{D}_J|\}$ to detect index $\hat{u}_t$. The index detecting algorithm is different according to the modulation mode of the modulated bits applied in the transmitter. If the amplitude of SPS is 2, i.e. the modulation modes applied by the transmitter is shown as Fig.1(a) or Fig.1(b), the index detection block finds the symbol with maximal energy, i. e., $\hat{u}_t$ is estimated as

$$\hat{u}_t = \arg \max_{t=1,\cdots,J} |\hat{D}_t| \tag{8}$$

If the transmitter applies the modulation modes as shown in Fig.1(c), the amplitude of SPS is 1, and the imaginary part of DM-constellation is zero. The index detection block finds the symbol with minimal imaginary part, i.e., $\hat{u}_t$ is calculated as

$$\hat{u}_t = \arg \min_{t=1,\cdots,J} \mathrm{Im}(\hat{D}_t) \tag{9}$$

where $\mathrm{Im}(\cdot)$ denotes the imaginary part of input.

Once $\hat{u}_t$ is estimated, the constellation symbol $\hat{s}(i, \hat{u}_t)$ can be regarded as SPS, thus a secondary CIR h_2 can be calculated according to SPS.

$$h_2(l) = \frac{v(\hat{u}_t, l)}{Ms(\hat{u}_t)} \tag{10}$$

Denoting $\hat{\mathbf{H}}(i)$ as the over all CIR in a DM-MSSS-IM transmitting block,

$$\hat{\mathbf{H}}(i) = \frac{\mathbf{h_1}(i) + \mathbf{h_2}(i)}{2} \tag{11}$$

the despreading block 2 recovers $(J-1)$ constellation symbols according to $\hat{\mathbf{H}}(i)$,

$$\hat{s}(i,j) = \frac{\sum_{l=1}^{L} \hat{\mathbf{H}}^*(l)v(j,l)}{M||\hat{\mathbf{H}}(l)||^2}, (j \neq u_t) \tag{12}$$

where $M||\hat{\mathbf{H}}(l)||^2 = M\sum_{l=0}^{L} |\hat{\mathbf{H}}(l)|^2$. After introducing h_2 into channel estimation, $\hat{s}(i,j)$ denotes the constellation of the j^{th} spreading sequence acquired by the despreading block 2.

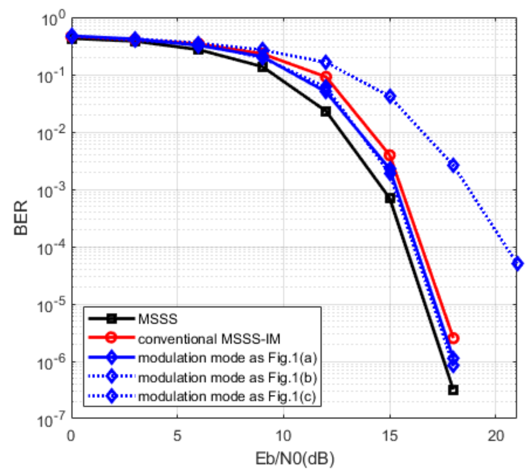

Fig. 5: The comparison of BER performance between the DM-MSSS-IM system and existing MSSS-IM system. $M = 1023$, $L = 100$, $J_{max} = 10$, $J = 9$

The index u_t is sent to the decimal to the binary converter and recovered to the mapped bits. J spreading sequences are sent to the despreading block 2, rectified based on $\hat{\mathbf{H}}$, and then despreaded into J constellation symbols $\{\hat{s}(i,1), \cdots, \hat{s}(i,J)\}$. The constellation symbols will be sent to the dual-mode demodulation block and converted to $(M_c \times J)$ modulated bits according to the modulation mode adopted in the transmitter. After combining the mapped bits and modulated bits, the corresponding transmitted signals are recovered at last.

III. Results and Discussions

A. Performance over Rayleigh Channel

In this section, the baseband BER performance of the DM-MSSS-IM system over the time-varying Rayleigh channel is evaluated via Monte Carlo simulation. The average power gains of each multi-path are uniformly distributed. The time delay of each multi-path is set to $\{\tau_l\}_{l=1}^{L} = [0, \cdots, L-1]T_c$, T_c is chip duration.

Figure.5, Fig.6, and Fig.7 compare the BER performance of the DM-MSSS-IM system with different modulation modes when M is 1023, M is 2047, and M is 4095, respectively. It is evident that

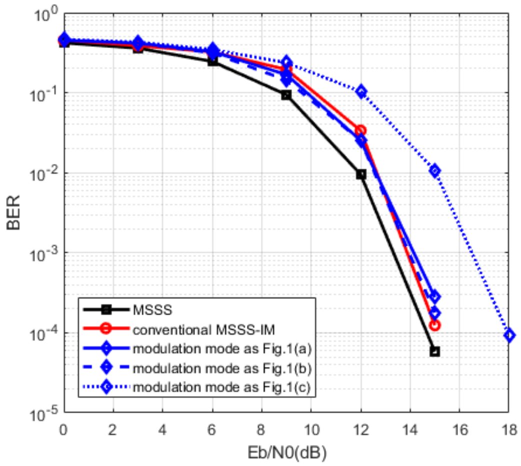

Fig. 6: The comparison of BER performance between the DM-MSSS-IM system and existing MSSS-IM system. $M = 2047$, $L = 100$, $J_{max} = 20$, $J = 19$

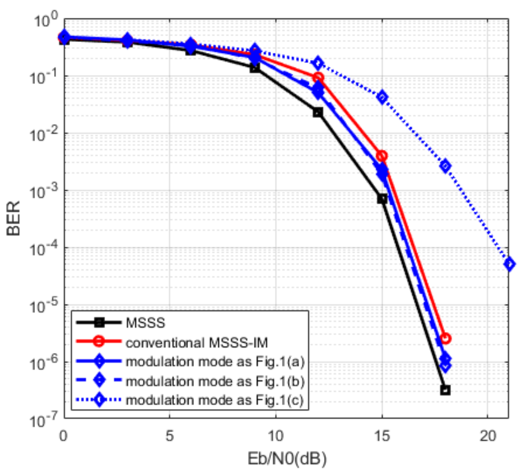

Fig. 7: The comparison of BER performance between the DM-MSSS-IM system and existing MSSS-IM system. $M = 4095$, $L = 100$, $J_{max} = 40$, $J = 39$

although the modulation mode shown in Fig.1(b) obtain a slight BER gain better than the modulation mode shown in Fig.1(a), the latter achieves the best trade-off between data rate and BER performance. Therefore, the following simulation of the DM-MSSS-IM system adopts the modulation mode as Fig.1(a).

TABLE I shows the comparisons of the data rate of MSSS, MSSS-IM, and DM-MSSS-IM systems over different lengths of spreading sequence. The data rate is evaluated by the number of bits carried per transmission block.

B. Performance over UWA Channel

In this subsection, we analyze the performances over the UWA simulation channel. To measure the BER performance of the proposed DM-MSSS-IM system, we conducted a simulation over the Watermark platform and a sea trial over Wuyuan Bay.

TABLE I: Data rate comparison between different schemes

Data rate / Scheme / length M	MSSS	MSSS-IM	DM-MSSS-IM
$M = 1023$	18	19	21
$M = 2047$	38	40	42
$M = 4095$	78	81	83

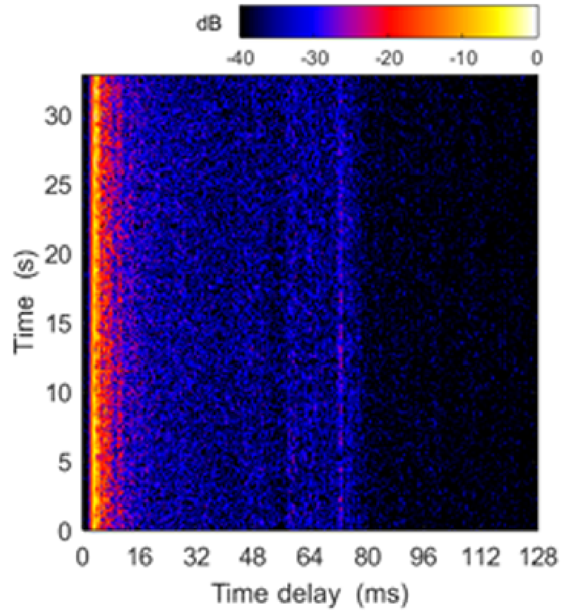

Fig. 8: CIR based on the simulation UWA channel model.

The UWA channel of Watermark is based on Watermark experimental platform. The simulation channel chosen is NOF1, measured in a shallow stretch of Oslofjorden in Norway between a stationary source and a stationary single-hydrophone receiver. More details about the NOF1 channel can be found in [9].

The channel model is based on beam tracing tools and built around the validated channel simulator 'MIME' (seen in [10]). The range between the transmitter and receiver is 750m, and the water depth is about 10m. The frequency band is from $10kHz$ to $18kHz$ with a center frequency of $14kHz$. The parameters J and L are the same as the Rayleigh channel. Fig.8 shows the CIR of the NOF1 simulation channel.

Figure 9 depicts the BER performance of the proposed DM-MSSS-IM system, conventional MSSS-IM system, and MSSS system. The SNR shown in Fig.9 is defined as $(\mathrm{SNR})_{\mathrm{dB}} = (\mathrm{E_{chip}}/\mathrm{N_0})_{\mathrm{dB}}$,

$$(\mathrm{E_{chip}}/\mathrm{N_0})_{\mathrm{dB}} = (\mathrm{E_b}/\mathrm{N_0})_{\mathrm{dB}} - 10\log_{10}(M) \qquad (13)$$

An ocean acoustic communication trial at Wuyuan Bay is conducted to verify the feasibility of the proposed DM-MSSS-IM system. The distance between the transmitter and the receiver is about 1km, and the depth is about 2m. TABLE II shows the

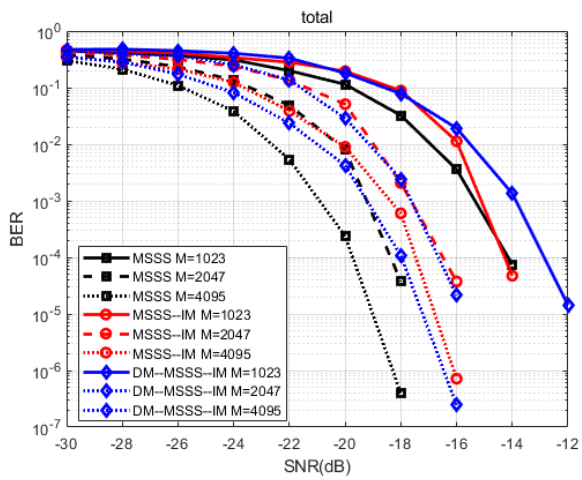

Fig. 9: The comparison of BER performance between proposed DM-MSSS-IM system, existing MSSS-IM system, and conventional MSSS system. $L = 100$

BER performance over Wuyuan Bay. The total transmission bits of each system are shown in the TABLE III.

It has conclusively been shown that the system's performance in the simulated UWA channels is roughly the same as that of the Rayleigh channel. When M is 1023, the BER performance of the DM-MSSS-IM system is not as good as that of the existing MSSS-IM system, whereas when M is 2047, the performance of the DM-MSSS-IM system is comparable to that of current MSSS-IM system. When M is 4095, the BER performance of the DM-MSSS-IM system is better than that of the MSSS-IM system.

Similar to the traditional spread-spectrum communication system, the larger the spreading factor, the better the BER performance of the system. The BER performance of the DM-MSSS-IM system is taking a turn for the better with the increase of the spreading factor M. The result of this study shows that the proposed DM-MSSS-IM system achieves a higher data rate at the cost of BER performance. The BER performance is not as good as the MSSS-IM system, but the former conveys more bits than the latter. MSSS system has the best BER performance and the lowest data rate. However, the proposed DM-MSSS-IM system achieves a higher data rate.

TABLE II: BER performance of Wuyuan Bay trial in July, 2022

BER \ Scheme / length M	DM-MSSS-IM	MSSS	MSSS-IM
$M = 1023$	0.01578947368	0.07553022104	0.08226315789
$M = 2047$	0.00291666667	0.00166666667	0.00750000000
$M = 4095$	0	0	0

TABLE III: Total transmission bits of Wuyuan Bay trial in July, 2022

Total bits \ Scheme / length M	DM-MSSS-IM	MSSS	MSSS-IM
$M = 1023$	630	540	570
$M = 2047$	1260	1140	1200
$M = 4095$	2490	2340	2430

IV. Conclusions

This paper proposes a dual-mode MSSS system with index modulation aided by a secondary pilot symbol for underwater acoustic communication. In the proposed system, the indexes of superimposed spreading sequences are used to carry information bits. Therefore, the proposed system achieves a higher data rate than the existing MSSS and MSSS-IM systems. Simulation results in time-varying Rayleigh channel and underwater acoustic channels verify that the proposed system has a better trade-off between data rate and BER performance over the existing MSSS and MSSS-IM systems. Furthermore, the first mode symbol is used as a secondary pilot symbol to improve channel estimation.

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