2023 Asia Communications and Photonics Conference/2023 International Photonics and Optoelectronics Meetings (ACP/POEM) | 979-8-3503-1261-4/23/$31.00 ©2023 IEEE | DOI: 10.1109/ACP/POEM59049.2023.10368765

22.5 Gbps UOWC Using WDM/PolM and OFDM with Interleaved Subcarrier Number Modulation

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***Abstract*—A 22.5-Gbps UOWC system using WDM/PolM is demonstrated, where OFDM with interleaved subcarrier number modulation (OFDM-ISNM) is proposed to extend the usable bandwidth. Experimental results show a 78.6% bandwidth extension by OFDM-ISNM compared with OFDM.**

***Index Terms*—Underwater optical wireless communication (UOWC), orthogonal frequency-division multiplexing (OFDM), interleaved subcarrier number modulation (ISNM).**

I. INTRODUCTION

OPTICAL wireless communication (OWC) is widely recognized as a promising communication technology for underwater environments, due to its inherent advantages such as sufficient spectrum resources, low latency, small size and high security [1]. Nevertheless, practical underwater OWC (UOWC) systems are usually bandlimited, due to the low-pass nature of commercially available optical components such as laser diodes (LDs) and photo-diodes (PDs) [2]. There are generally two ways to address the bandwidth limitation issue of practical UOWC systems: one is to directly extend the usable bandwidth of the system, and the other is to increase the number of bits that can be transmitter per unit bandwidth, i.e., spectral efficiency. For usable bandwidth extension, various pre- or post-equalization schemes have been proposed [3]–[5]. However, pre-equalization generally requires the feedback of channel information which might also be vulnerable to LED nonlinearity [6], while post-equalization usually has a high computational complexity. For spectral efficiency enhancement, orthogonal frequency-division multiplexing (OFDM) modulation, polarization multiplexing (PolM), wavelength division multiplexing (WDM) and spatial division transmission (SDT) schemes can be applied [7]–[9].

In this paper, we propose and experimentally demonstrate a novel OFDM scheme, i.e., OFDM with interleaved subcarrier number modulation (OFDM-ISNM), for usable bandwidth extension in a hybrid WDM/PolM based UOWC system. By performing subcarrier number modulation (SNM) with interleaving, the system usable bandwidth can be efficiently extended and the overall achievable data rate can be significantly improved.

This work was supported by the National Natural Science Foundation of China under Grant 62271091.

TABLE I
MAPPING TABLE FOR SNM

Information bits	No. of activated subcarriers	Subblock vector
000000	0	[0, 0, 0, 0]
000001	1	[S_1, 0, 0, 0]
···	···	···
001000	1	[S_8, 0, 0, 0]
001001	2	[S_1, S_1, 0, 0]
···	···	···
010000	2	[S_1, S_8, 0, 0]
010001	2	[S_2, S_1, 0, 0]
···	···	···
111111	2	[S_7, S_7, 0, 0]

II. PRINCIPLE

We first introduce the principle of OFDM-ISNM. Fig. 1(a) illustrates the principle of the OFDM-ISNM transmitter, where the subcarriers are divided into subblocks and SNM is performed within each subblock. Let N and k denote the size of the subblock and the number of the activated subcarriers within each subblock, respectively. For a large k, the subblock can transmit more M-ary constellation symbols, but suffers from a more severe low-pass effect. For a small k, the subblock can experience a less severe low-pass effect, but transmits a reduced number of constellation symbols. To achieve a trade-off between data rate and low-pass effect, the k set is assumed to be $k \in \{0, 1, 2\}$ for $N = 4$ in this demonstration. Table I gives the mapping table for SNM with $N = 4$, $k \in \{0, 1, 2\}$

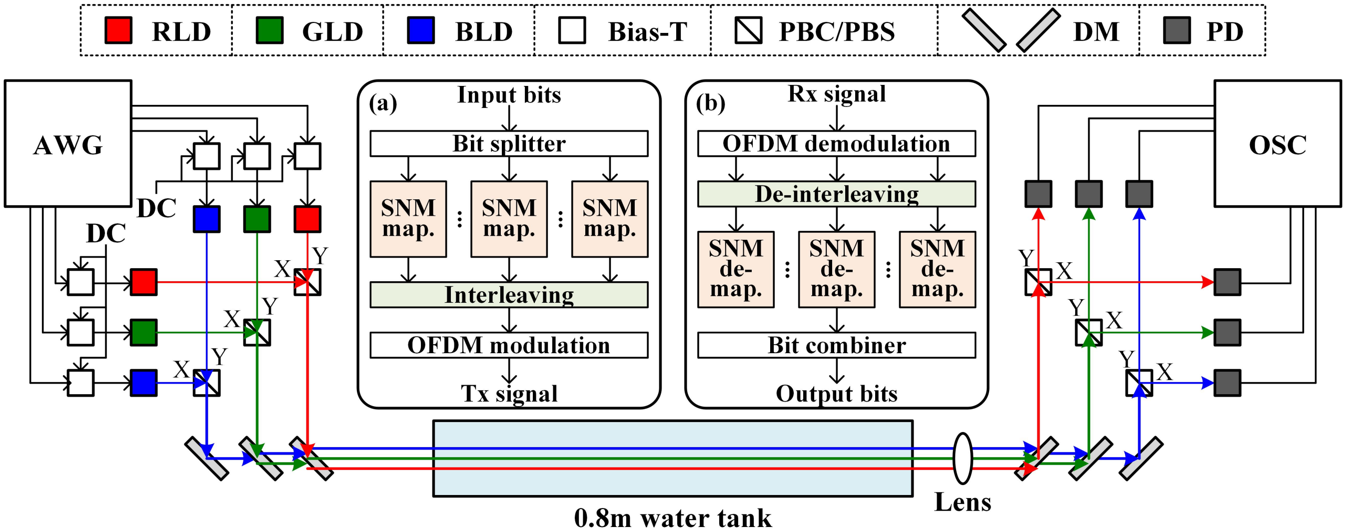

Fig. 1. Experimental setup of the UOWC system using hybrid WDM/PolM and OFDM-ISNM. Insets: principle of (a) OFDM-ISNM transmitter and (b) OFDM-ISNM receiver.

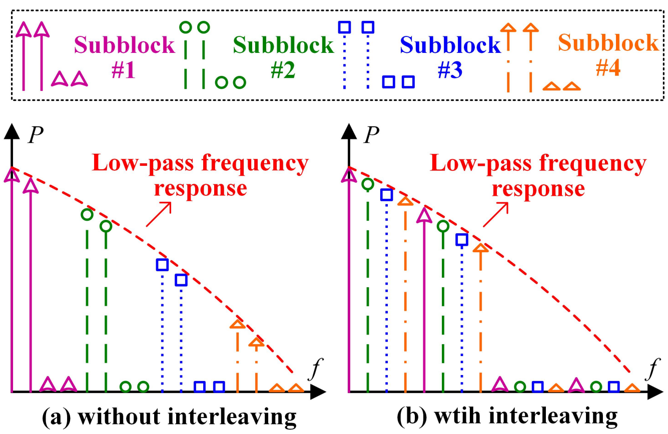

Fig. 2. Illustration of the received OFDM-SNM spectrum: (a) without interleaving and (b) with interleaving.

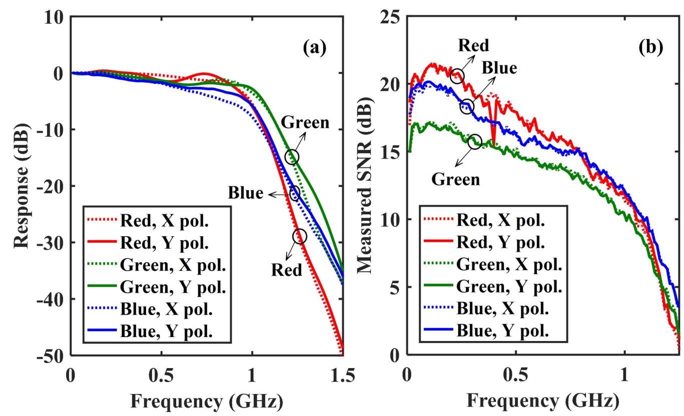

Fig. 3. Characterization of the hybrid WDM/PolM based UOWC system: (a) response and (b) measured SNR.

and $M = 8$, which is corresponding to a spectral efficiency of 1.5 bit/s/Hz.

After SNM mapping, interleaving is conducted among different subblocks. Figs. 2(a) and (b) illustrate the received OFDM-SNM spectrum without and with interleaving, respectively, where $N = 4$ and $k = 2$. Without interleaving, the activated subcarriers are separately distributed over the entire system bandwidth, which experience a severe low-pass effect. In contrast, with interleaving, all the activated subcarriers are located within the low-frequency region of the system bandwidth and hence the adverse low-pass effect can be significantly mitigated. Finally, OFDM modulation is executed to obtain the signal for transmission.

The principle of the OFDM-ISNM receiver is depicted in Fig. 1(b), where the received OFDM signal is first demodulated and then de-interleaving is performed to recover the subblocks. After that, SNM de-mapping is carried out via maximum-likelihood (ML) detection to achieve optimal performance. Subsequently, the output bits can be obtained via a bit combiner.

III. Experimental Setup

The experimental setup of the UOWC system using hybrid WDM/PolMux and OFDM-ISNM is depicted in Fig. 1, where three wavelength channels (i.e., the red, green and blue channels) are established by using red LDs (RLD, HL6544FM), green LDs (GLD, PL520) and blue LDs (BLD, PL450b). Moreover, two orthogonal polarization channels are further configured over each wavelength channel. The frequency response and the measured signal-to-noise ratio (SNR) of the hybrid WDM/PolM based UOWC system are presented in Figs. 3(a) and (b), respectively. As we can see, all the wavelength channels exhibit a low-pass characteristic and the corresponding -3dB bandwidths are all below 1 GHz.

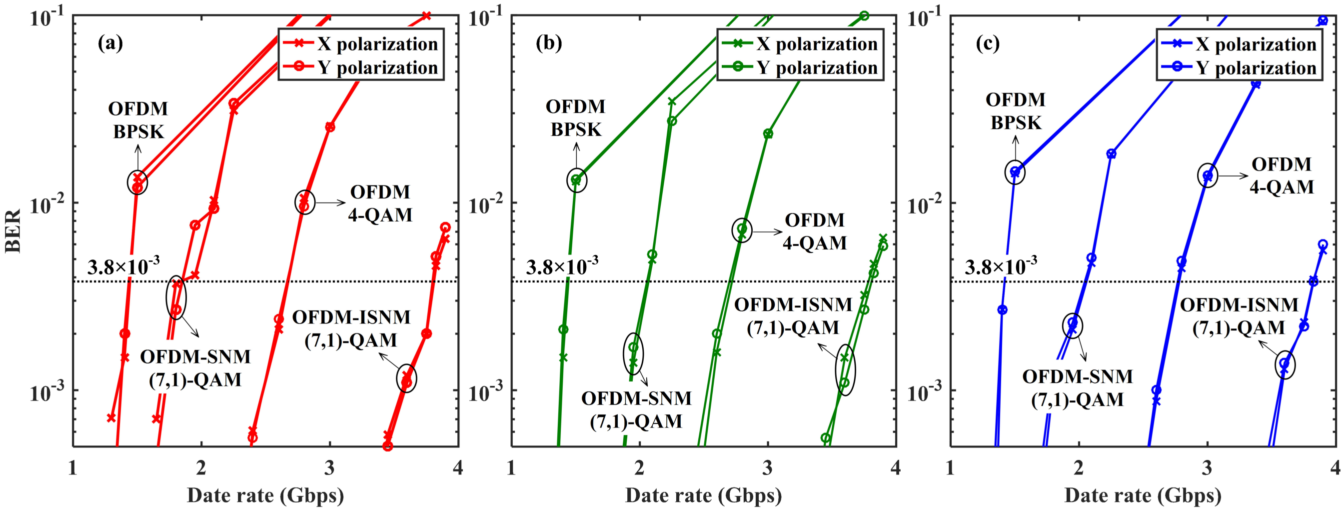

Fig. 4. Measured BER versus data rate for the hybrid WDM/PolM based UOWC system using different modulation schemes through (a) the red channel, (b) the green channel, and (c) the blue channel.

The digital OFDM-ISNM signals are generated offline by MATLAB, where the length of IFFT/FFT is 256 and the number of data subcarriers is 108. Moreover, a special-shaped 8-ary constellation, i.e., circular (7,1)-QAM constellation, is adopted [10]. The digital signals are loaded into arbitrary waveform generators (AWG, AWG7000A, Tektronix) and the bandwidth/data rate of the generated signals can be adjusted by changing the AWG sampling rate. The generated analog signals are combined with DC biases via bias-Ts.

After hybrid wavelength/polarization multiplexing, the optical signal propagates through a 0.8-m water tank filled with tap water. At the receiver side, a convex lens is used to focus the light and hybrid wavelength/polarization de-multiplexing is performed. Subsequently, six avalanche PDs (APD, Menlo Systems APD210) with 1-GHz bandwidth are used to detect the optical signals, and the detected signals are recorded by the oscilloscope (OSC, Tektronix MSO73304DX) for further offline demodulation.

IV. Experimental Results

We measure the BER performance of the hybrid WDM/PolM based UOWC system using different modulation schemes. The BER versus data rate for the hybrid WDM/PolM based UOWC system through different wavelength channels is shown in Fig. 4. As we can observe, both the X and Y polarization channels over one wavelength channel have nearly the same BER performance. For the red channel, the maximum data rates for X and Y polarization channels using OFDM-BPSK are both 1.4 Gbps, suggesting a maximum usable bandwidth of 1.4 GHz. By replacing OFDM-BPSK with OFDM-4QAM, the maximum data rates for X and Y polarization channels are increased to 2.7 Gbps, and the corresponding maximum usable bandwidth is still 1.4 GHz. However, when the proposed OFDM-ISNM scheme with (7,1)-QAM constellation is applied, the maximum data rates for X and Y polarization channels are significantly improved to 3.8 Gbps, which correspond to a maximum usable bandwidth of up to 2.5 GHz. In contrast, for OFDM-SNM without interleaving, the maximum data rates for X and Y polarization channels are only 1.8 Gbps, and the corresponding maximum usable bandwidth is only 1.2 GHz. Hence, interleaving is vital for the proposed OFDM-ISNM scheme to achieve superior performance than conventional OFDM. It can be further seen from Fig. 4 that the green and blue channels can achieve comparable performance as the red channel, which is mainly because the system bandwidth is limited by the APDs instead of the red, green and blue LDs.

TABLE II
Comparison of Different Modulation Schemes

Modulation scheme	Usable bandwidth	Achievable data rate
OFDM BPSK	1.4 GHz	8.4 Gbps
OFDM 4-QAM	1.4 GHz	16.8 Gbps
OFDM-SNM (7,1)-QAM	1.3 GHz	11.7 Gbps
OFDM-ISNM (7,1)-QAM	2.5 GHz	22.5 Gbps

Table II gives the comparison of different modulation schemes in terms of average usable bandwidth and overall achievable data rate. Compared with conventional OFDM with BPSK and 4-QAM, the usable bandwidth can be extended from 1.4 GHz to 2.5 GHz by applying OFDM-ISNM with (7,1)-QAM constellation, indicating a remarkable bandwidth extension of 78.6%. The overall data rate of the hybrid WDM/PolM based UOWC system applying OFDM-ISNM with (7,1)-QAM constellation reaches 22.5 Gbps.

V. Conclusions

We have proposed and demonstrated an OFDM-ISNM scheme for efficient bandwidth extension in a hybrid

WDM/PolM based UOWC system, achieving an overall data rate of 22.5 Gbps. Compared with conventional OFDM, a 78.6% bandwidth extension is achieved by OFDM-ISNM.

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