Performance Enhanced Polmux-UOWC Using Subcarrier and Subchannel Joint Pairwise Coding

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***Abstract*—We propose and experimentally demonstrate a subcarrier and subchannel joint pairwise coding scheme for polarization multiplexing underwater optical wireless communication. The overall transmission data rate is improved by 24.3% at 7% FEC threshold.**

Keywords—under water optical wireless communication, polarization division multiplexing, pairwise coding

I. INTRODUCTION

A promising solution for developing the next generation of underwater communication links is underwater optical wireless communication (UOWC), which has various attractive advatages over underwater acoustic communication (UAC), such as high transmission data rate, low power consumption and cost-effectiveness [1]. However, UOWC system capacity is still restricted by system bandwidth limitation. Therefore, techniques including polarization multiplexing (PolMux) together with orthogonal frequency-division multiplexing (OFDM) [2], have been demonstrated to address this issue. In a PolMux-OFDM UOWC system, two serials independent data can be modulated on mutually perpendicular polarization light beams to synthesize polarization multiplexed signal, which directly doubles the transmission capacity. In most multi-channel optical wireless conmmunication systems, the system bandwidth limitation results in a low-pass frequency response effect, which reduces the signal quality at higher frequency subcarriers [3]. This results in an imbalance in the received signal-to-noise-ratio (SNR) between received subcarriers (SCs). As investigated in [4], this issue can be effectively alleviated by the subcarrier pairwise coding (SC-PWC) technique with a simple structure and low computational complexity. SC-PWC refers to implementing PWC to SCs of OFDM frames, namely the frequency dimension, which interleaves the low-frequency and high-frequency subcarriers from the same subchannel (SCH). On the other hand, system alignment, turbulence, turbidity and bubbles will also introduce SNR imbalance between two polarization multiplexed subchannels. SCH-PWC is employed to mitigate this issue as demonstrated in our previous work [5]. SCH-PWC is the application of PWC between subchannels, namely spatial dimension. For SCH-PWC, the subcarriers with the same index from two PolMux subchannels are paired together and then interleaving can be performed with respect to those subchannel pairs.

In this work, we propose a subcarrier and PolMux subchannel joint pairwise coding (FCH-PWC) scheme which performs PWC with respect to both subcarriers in the frequency domain and subchannels in the polarization domain to mitigate the impairment of low-pass frequency response and SNR imbalance of polarization multiplexed subchannels. FCH-PWC can further improve the transmission data rate and robustness of the PolMux system confronted with limitation bandwidth and complex underwater channels.

II. PRINCIPLE AND EXPERIMENTAL DEMONSTRATION

A. Principle of FCH-PWC

The principle of FCH-PWC is illustrated in Fig. 1. First, the quadrature amplitude modulation (QAM) mapped signals in all subcarriers of two polarizations are sorted by channel gains obtained from received signal frequency domain

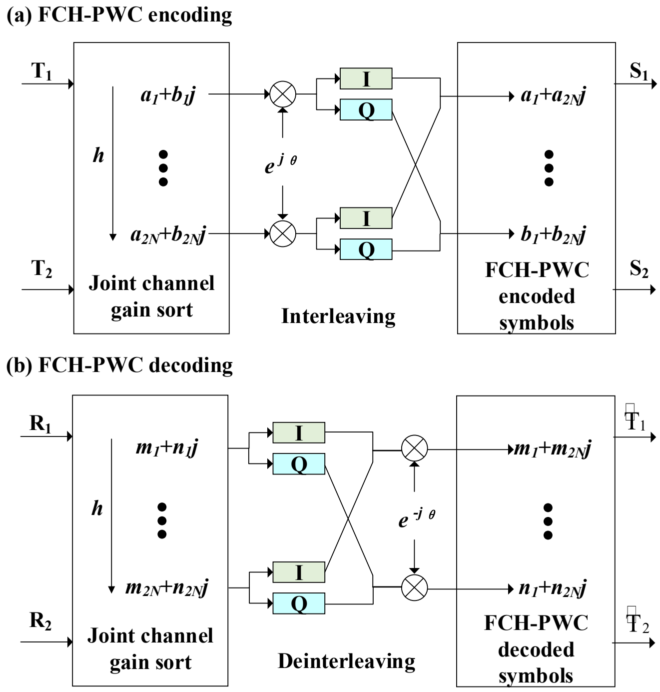

Fig. 1. Principle of subcarrier and subchannel joint pairwise (a) encoding and (b) decoding.

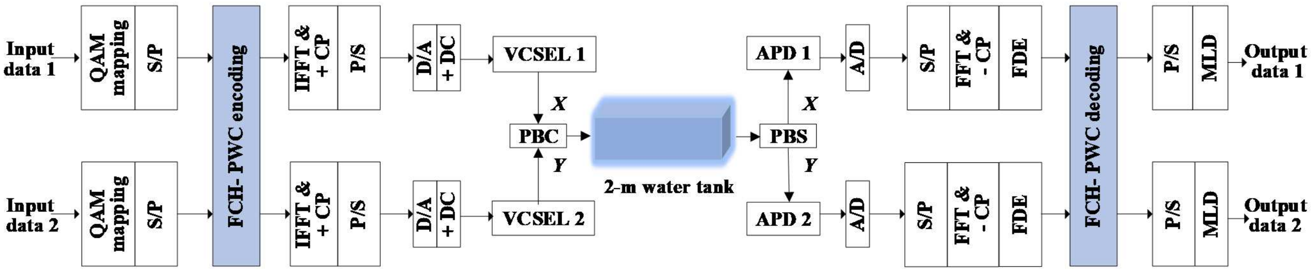

Fig. 2. Schematic of the experimental setup

equalization (FDE). It is assumed that the channel information is known at the Tx side. Then, the sorted subcarriers are paired and interleaved according to the obtained order. For example, i-th pair of subcarriers can be demonstrated as: (S_i, S_{2N-i+1}), i =1, 2, … , N, where N is the number of data subcarriers in one OFDM scheme. Furthermore, a constant phase shift θ is applied to the modulated quadrature amplitude modulation (QAM) signals. The optimal rotation angle is usually obtained based on the degree of imbalance between the subcarriers with good and bad SNR. Next, the in-phase (I) and quadrature (Q) components of two channels are separated and interleaved. Then, all the subcarriers are paired and interleaved according to the obtained sorted order. The i-th pair can be demonstrated As for FCH-PWC decoding process demonstrated in Fig. 1(b), deinterleaving is performed according to the sorting order array employed in the encoding process. Finally, the received QAM symbols are obtained by maximum likelihood detection (MLD). Basic SC-PWC and SCH-PWC perform subcarrier pairing and interleaving in the frequency and polarization domain, respectively. Through interleaving, the SNR imbalance between the paired SC/SCHs transfers to the I and Q components of the symbols modulated on the SC/SCHs. FCH-PWC scheme is proposed to combine both aforementioned dimensions for interleaving. As a result, it can reduce the impact of bandwidth limitation and imbalance between the two channels simultaneously, therefore improving the robustness of the PolMux UOWC system. Besides, it can always achieve bit error rate (BER) improvements over basic OFDM as long as the two PolMux signals have imbalanced SNRs.

B. Experimental Setup

The architecture of the PolMux-UOWC system employing different PWC techniques is presented in Fig. 2. Firstly, the random transmission data are mapped to 8-QAM signals and serial-to-parallel (S/P) conversion is performed. The following step is FCH-PWC encoding, inverse fast Fourier transform (IFFT), cyclic prefix (CP) insertion and parallel-to-serial (P/S) conversion. The size of the IFFT is 1024, and out of which, 238 are modulated with data. Two serials modulated and encoded data are loaded to the arbitrary waveform generator (AWG, AWG7000A, Tektronix) and combined with direct current (DC) components using a bias-tee (ZFBT-6GW+, Mini-circuit). The light source is an essential component of UOWC, which can be realized by vertical cavity surface emitting lasers (VCSEL) array with compact size and low threshold current [6].Two VCSELs (DV0680M, DERAY) with center wavelength at 680 nm are chosen as the optical transmitter. Then two emitting light beams are converged by a polarization beam combiner (PBC). After passing through two plano-convex lenses, the polarization multiplexed beam propagates through a 2-m water tank (width: 0.8 m, height: 0.4 m) filled with tap water. At the receiver (Rx), the light beam is separated by a polarization beam splitter (PBS) and detected by two avalanche photodiodes (APDs, APD210, Menlo Systems). Finally, the output electrical signals are obtained by a real-time oscilloscope (RTO, MSO73304DX, Tektronix) with a sampling rate of 25 GSa/s. FDE is implemented to obtain the channel gain coefficient sorting order sequence. Then, FCH-PWC decoding is exploited to the two serials received signals following with S/P conversion, FFT and CP removal. Finally, the initially transmitted data is obtained by performing P/S conversion and MLD. The frequency response of the whole PolMux UOWC system is measured by a vector network analyzer (VNA, N5227A, Agilent).

III. Results and Discussions

The normalized frequency response of the employed PolMux-UOWC system with different polarization states are presented in Fig. 3. The 3dB modulation bandwidth of X and Y is 0.855 GHz and 0.858 GHz, respectively. It is worth noting that the steep roll-off of the frequency response is mainly caused by the bandwidth limitation of the APD which has a 3dB modulation bandwidth of 1 GHz at the Rx side. By changing the alignment of VCSEL-APD, unideal PolMux-UOWC system with SNR imbalance between two subchannels can be simulated. SNR distributions of received signals with polarization states: X and Y are demonstrated in Fig. 4. The value of ΔSNR = 3.95 dB presents that the PolMux subchannels faces a certain degree of SNR imbalance except from the limited system bandwidth.

To demonstrate the effectiveness of our proposed FCH-PWC scheme, the communication performance of the uncoded and different PWC schemes is shown in Fig. 5 with the plot of the BER at different transmission data rates. In all the BER results, it is clear that FCH-PWC achieves the best BER performance among all the PWC schemes under different rates. And FCH-PWC achieves a 6.77 Gbps overall

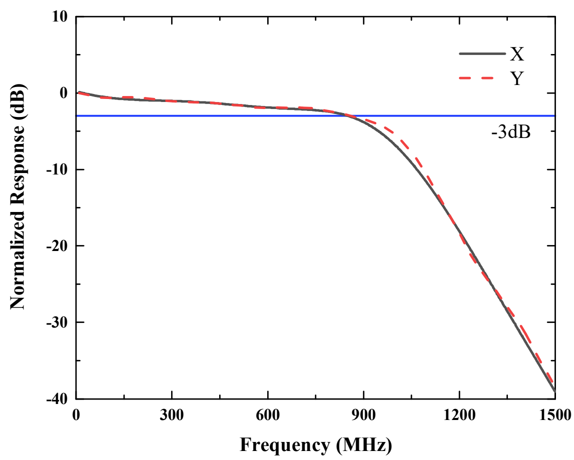

Fig 3. Frequency response of two PolMux UOWC subchannels.

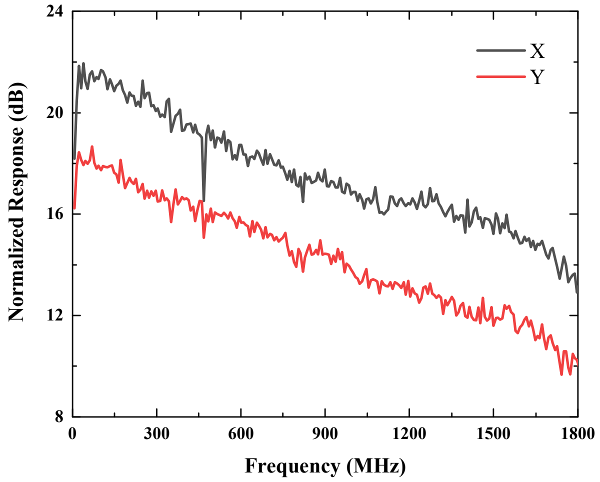

Fig 4. Received SNR distribution of polarization states: *X* and *Y*.

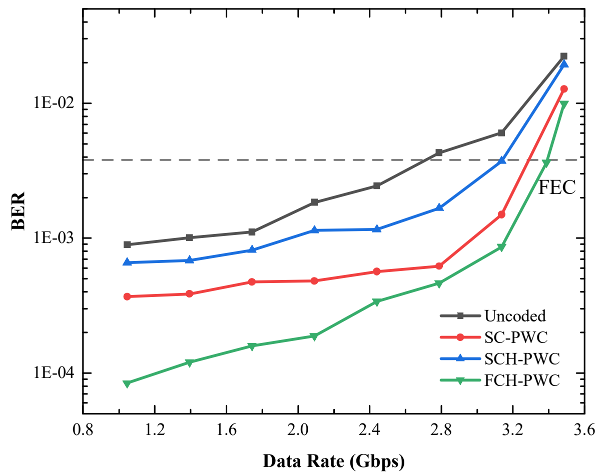

Fig 5. BER performance of different PWC schemes.

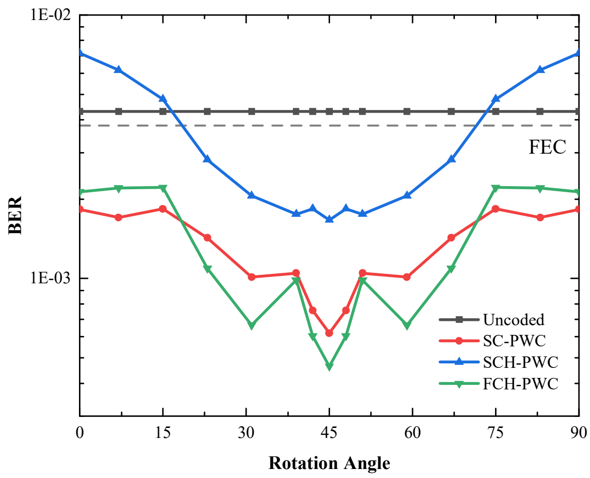

Fig 6. BER performance with different rotation angles

data rate at the 7% forward error correction (FEC) coding limit of BER = 3.8×10^{-3}. A significant data rate improvement of 24.3% is obtained by FCH-PWC, while 15.8% and 19.5% by SCH-PWC and SC-PWC over the basic 8-QAM OFDM to reach the FEC.

In addition, this work experimentally investigates the effect of the PWC rotation angle on communication performance. The adaptive PWC requires immediate channel feedback, and the optimal rotation angle for adaptive PWC has been discussed analytically in [7]. 45°is preferable in most cases and can be derived by the SNR of the two paired subcarriers. We obtained the received BER by rotating different angles through PWC coding at the Tx with a data rate fixed at 2.79 Gbps. From the measured results demonstrated in Fig. 6, the BERs of SC-PWC and FCH-PWC can always reach the FEC limit with a rotation angle range from 0 to 90°. For ideal links, the optimal results can be obtained with 45° rotation angle, and the BER will monotonically increase with changing angle [8]. Nevertheless, due to the unideal aligned PolMux link employed in the above experiments, it can be seen that BER will first increase, then decrease and finally monotonically increase with the offset of the rotation angle, which results in two suboptimal rotation angles besides 45°. As a result, the SNR difference between the two subchannels affects the selection of the optimal rotation angle, and the rotation angle for PWC coding should be obtained according to the actual complex underwater channel.

IV. Conclusion

We propose a modified PWC scheme for PolMux UOWC links which simultaneously solves the issue of limited system bandwidth and PolMux subchannel SNR imbalance. An overall data rate of 6.67 Gbps is achieved through 2-m underwater transmission. Moreover, we demonstrate through experiments that the optimal rotation angle selection for PWC should be further determined by two subchannel SNR imbalance.

Acknowledgment

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