Experimental Demonstration of Bubble-induced Turbulence Compensation Employing NHS-PWC in PolMux-UOWC

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Abstract: We propose a non-Hermitian symmetric pairwise coding scheme to compensate for the impairments of bubble-induced turbulence in underwater optical wireless communication, and experimentally demonstrate an 8.58 Gbps system combined with polarization multiplexing.

1. Introduction

Combining polarization multiplexing (PolMux) with orthogonal frequency-division multiplexing (OFDM) has been demonstrated for high-capacity underwater optical wireless communication (UOWC) [1]. Two independent serial data can be modulated on mutually orthogonal polarized light beams, which directly doubles the system capacity. In most multi-channel OFDM optical transmission systems, the low-pass bandwidth profile with fluctuation results in an imbalance of received signal-to-noise-ratio (SNR) between subcarriers (SCs) [2]. This issue can be alleviated by subcarrier pairwise coding (SC-PWC) [3]. Besides, in PolMux-UWOC links, the effects of bubble-induced turbulence have rarely been investigated. According to experimental demonstration in this work, bubble-induced turbulence affects the orthogonality of the two PolMux signals, leading to the unbalanced SNR between subchannels. Moreover, misalignment and fish blocking will also introduce subchannel SNR imbalance. These effects can be mitigated by employing subchannel-PWC (SCH-PWC). Since both SC-PWC and SCH-PWC require Hermitian symmetry (HS) operation, which directly doubles system complexity and power consumption. Non-Hermitian symmetric OFDM (NHS-OFDM) is demonstrated to address this issue [4]. In addition, NHS-OFDM can always achieve bit-error-rate (BER) improvement when two OFDM signals have different SNRs. Therefore, it is significant and effective to combine NHS-OFDM with PWC in turbulent PolMux channels with subchannel SNR imbalance.

In this work, we assess the impact of bubble-induced turbulence on the PolMux-UOWC system and propose a non-Hermitian symmetric PWC (NHS-PWC) scheme with low computational complexity and power consumption, as well as better compensation performance to mitigate the impairments. The communication performance is compared with conventional PWC schemes. A significant BER improvement achieved in the bubble-induced turbulence channel presents the superiority of our proposed NHS-PWC scheme.

2. Principle and Experimental Setup

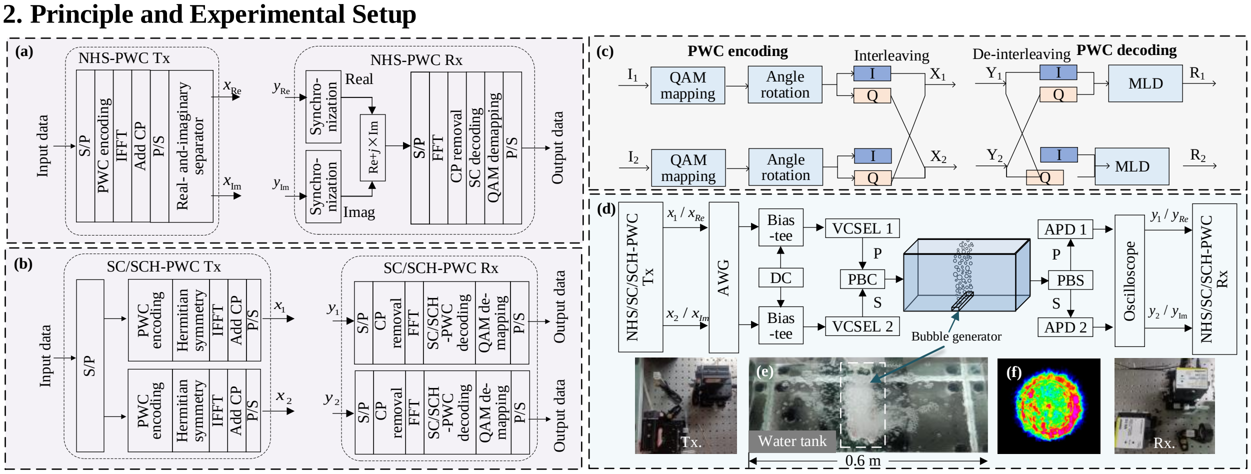

Fig. 1. System model of (a) NHS-PWC, (b) SC/ SCH-PWC, (c) illustration of PWC, (d) experiment setup, (e) lab-simulated bubble-induced turbulence channel and (f) charge coupled device (CCD) camera photograph of the distorted beam, inserted: Tx and Rx side.

The block diagrams of NHS-PWC transmitter (Tx) and receiver (Rx) are illustrated in Fig. 1(a). Firstly, the serial input data are converted to parallel bits and mapped into 16-quadrature amplitude modulation (QAM) symbols. Then PWC process is implemented as shown in Fig. 1(c), a constant phase shift is applied to increase the minimum Euclidean distance. Next, the in-phase (I) and quadrature (Q) components of the two channels are divided and interleaved, followed by IFFT and cyclic prefix (CP) insertion. Finally, the real and imaginary parts are separated to generate two serials of real-valued transmitted signal. At the Rx, received signals are recombined to construct the complex symbols after synchronization. Following serial-to-parallel (S/P) conversion, fast Fourier transform (FFT), and CP removal, the PWC decoding process is implemented, including I/Q de-interleaving and maximum likelihood detection (MLD). Subsequently, QAM demapping and parallel-to-serial (P/S) conversion are performed. Compared with SC-PWC and SCH-PWC illustrated in Fig. 1(b), HS operation needs to be applied before IFFT to generate a real-valued signal, exploiting two pairs of HS-OFDM Tx and Rx. Nevertheless, only one pair of Tx and Rx are set in NHS-OFDM, and there is no need for HS operation before IFFT. In conclusion, NHS-PWC eliminates the constraint of HS and achieves a more straightforward system structure and lower computational complexity.

An experimental demonstration of the PolMux-UOWC system employing different PWC is performed in Fig. 1(d). Firstly, two serials data with PWC are loaded to arbitrary waveform generator (AWG) with sampling rate: 4.5Gsamp/s, resulting in a sum data rate of 8.58 Gbps and combined with direct current components (DC) by bias-tee. Two beams generated by vertical cavity surface emitting lasers (VCSELs) are converged with a polarization beam combiner (PBC) to form the polarization multiplexed signal and propagate through a 0.6-m water tank. A bubble generator with a 0.70-L/s flow rate simulates the bubble channel in Fig. 1(e). At the Rx, the light beam is separated by a polarization beam splitter (PBS), detected by two avalanche photodiodes (APDs), and captured by an oscilloscope (OSC). Fig. 1(f) shows the one of the received distorted light beams.

3. Results and Discussions

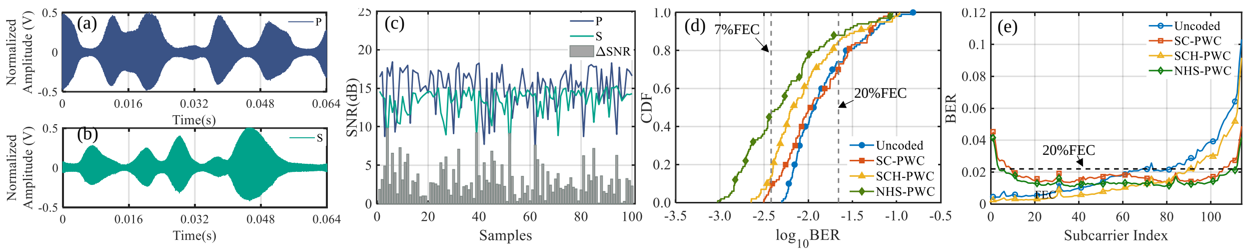

Fig. 2. (a) Normalized received waveform of different polarization direction denoted as parallel (P) and (b) senkrecht (S), (c) SNR results of collected samples, (d) CDF of measured BER results from collected samples and (e) BERs versus data SCs employing different schemes

The unideal PolMux-UOWC system with SNR imbalance between two subchannels can be imitated by adjusting the VCSEL-APD alignment. In Fig. 2(a) and (b), the waveforms of simultaneously detected received signals are different, which indicates that the bubble medium affects the polarization state of the light and thus has an impact on the orthogonality of the two polarization multiplexed signals. The SNR results of both polarization states and their difference with continuously collected 100 samples are shown in Fig. 2(c). The SNR values all fluctuate with time, affirming the waveform observation. Moreover, BERs of different PWC schemes and their cumulative distribution function (CDF) are calculated as shown in Fig. 2(c) with 20% FEC criteria (2.2×10^{-2}) and 7% FEC criteria (3.8×10^{-3}). All the PWC schemes provide channel compensation. In general, NHS-PWC achieves best compensation performance, which reduces the outage probability from 100% to 53%, while 92% by SC-PWC and 86% by SCH-PWC, assuming 7% FEC. In addition, BER variance from collected samples decreased from 6.04×10^{-4} to 3.05×10^{-4} exploiting NHS-PWC, reflecting a significant transmission reliability improvement. Furthermore, the BERs of OFDM data subcarriers obtained by collected samples are given in Fig. 2(e). Without coding, most errors occur at high frequency, and 29.8% of the subcarriers are above the 20% FEC. The BERs of SCH-PWC subcarriers are generally lower than the uncoded scheme but still terrible at high frequency. Nevertheless, by adopting NHS-PWC and SC-PWC, the BER performance of high frequency is effectively improved, while NHS-PWC outperforms SC-PWC in all data subcarriers with only 5.2% subcarriers are above the 20% FEC.

4. Conclusions

We experimentally investigated the interference of bubble-induced turbulence on PolMux-UOWC systems and demonstrated turbulence compensation by employing PWC schemes. Most importantly, NHS-PWC was proposed for further performance enhancement. The experimental results indicate that the impact of bubble-induced turbulence can be effectively mitigated by PWC, especially the proposed NHS-PWC.

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References

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